Lecture 14

EM: Grounded Sources

GEOL 4397: Electromagnetic Methods for Exploration
GEOL 6398: Special Problems

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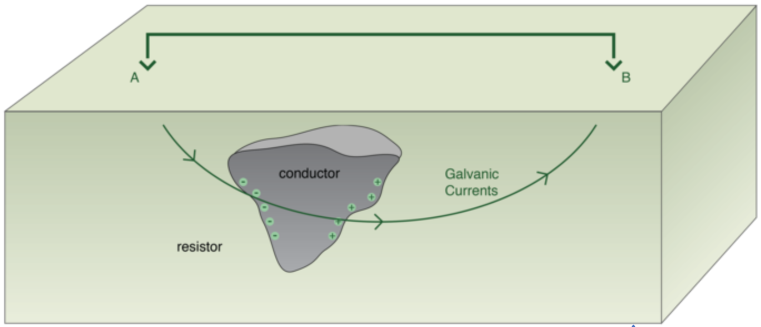
UNIVERSITY of HOUSTON
YOU ARE THE PRIDE
EARTH AND ATMOSPHERIC SCIENCES

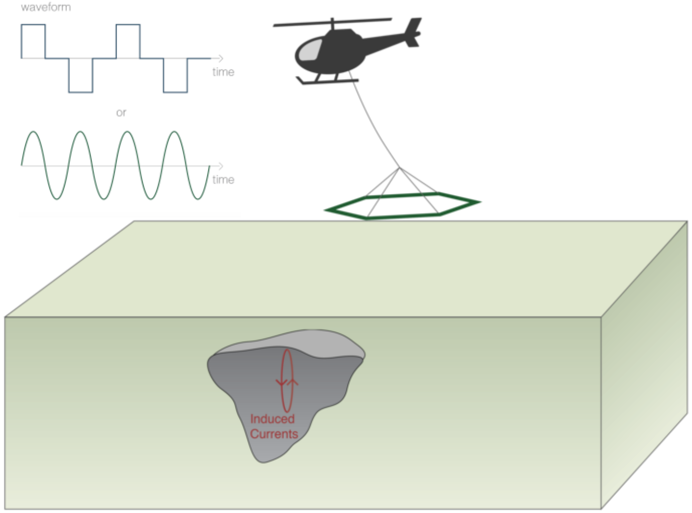
Agenda

- Grounded source EM: motivation
- Grounded source EM: halfspace
- Grounded source EM: with a conductive target
- Grounded source EM: with a resistive target
- Marine controlled source EM
- Case study: Barents Sea

From DC and inductive source to grounded source



DC resistivity



Inductive source

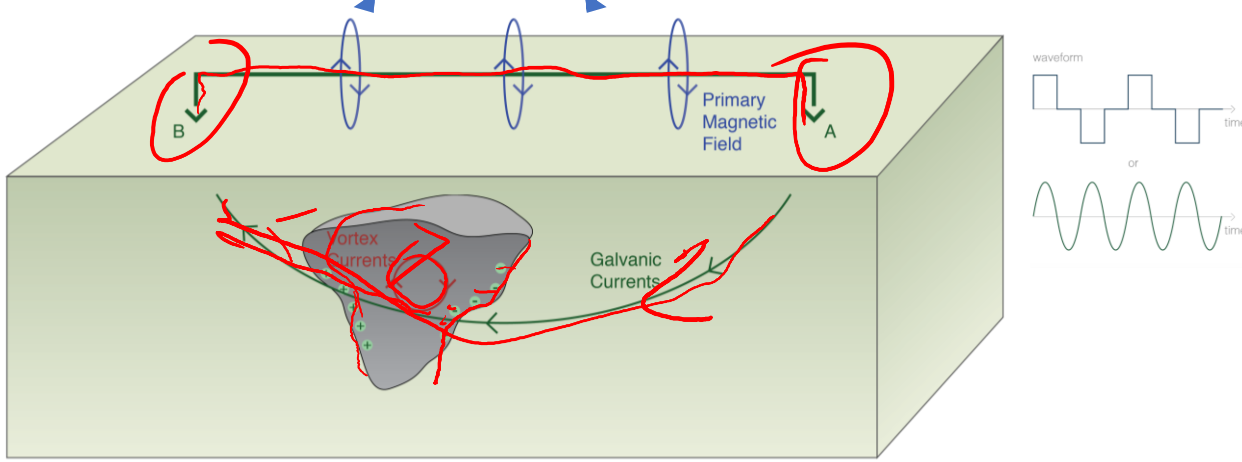
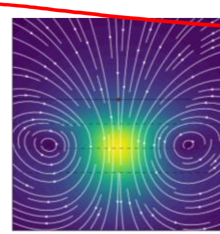


Image credit: Doug Oldenburg, Seogi Kang and Linsey Heagy from UBC-GIF

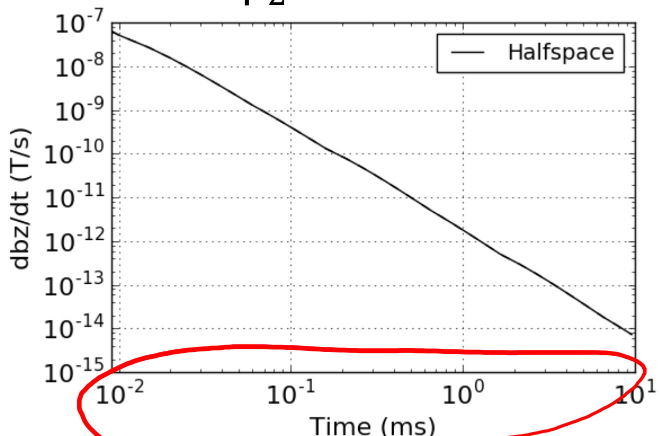
Question

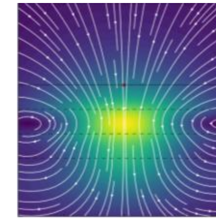
- Why bother with grounded sources?
- What is wrong with inductive source EM?

db_z/dt sounding curves for a layered Earth model from inductive source EM

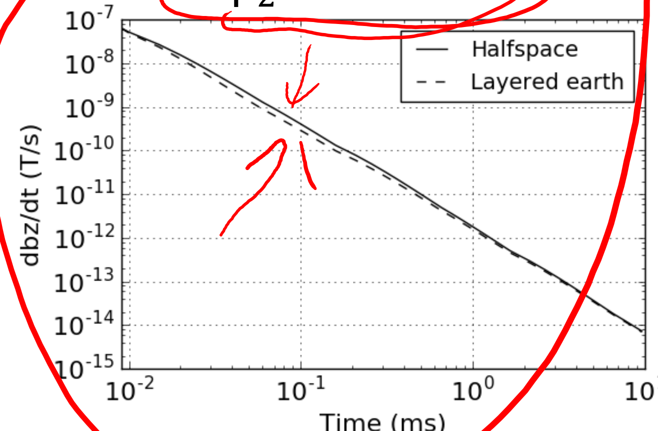


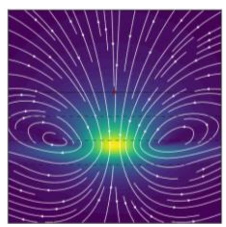
ρ_2 = 100 Ωm



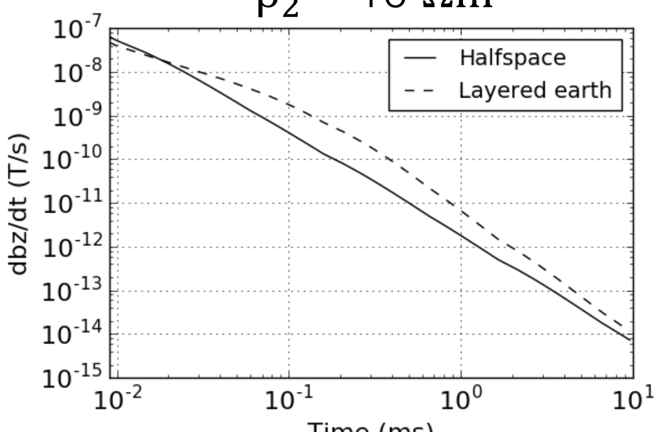


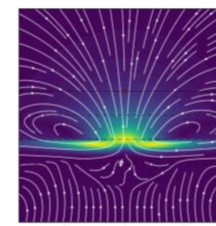
ρ_2 = 1000 Ωm



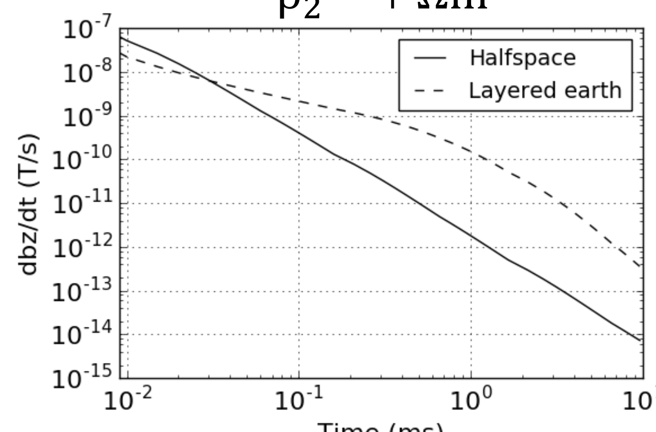


ρ_2 = 10 Ωm





ρ_2 = 1 Ωm



Observations

- EM signal decays slower in more conductive medium
- EM with inductive sources very sensitive to conductors (not so sensitive to resistors)

Question

- What if our target is a resistor?

Question

- What if our target is a resistor?
- Can you think of anything in geoscience that is resistive and of great economic value?

Question

- What if our target is a resistor?

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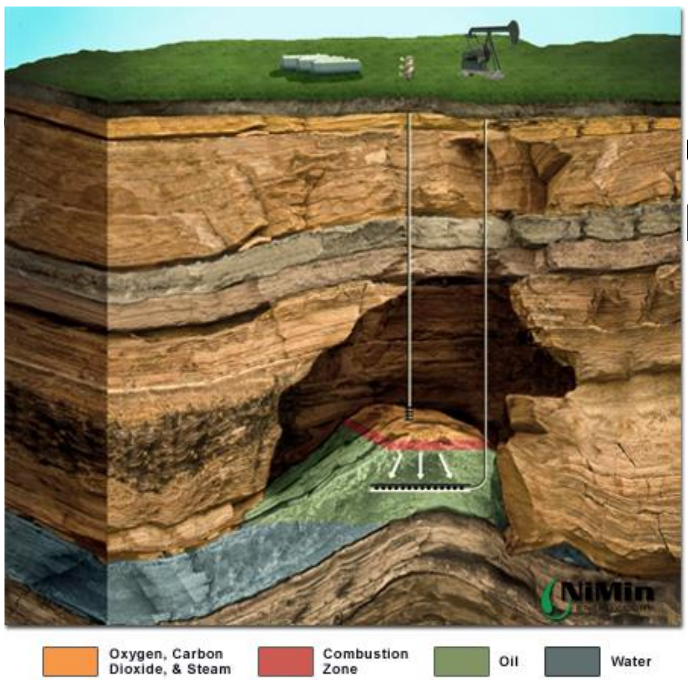


Oil and Gas

Methane Hydrates

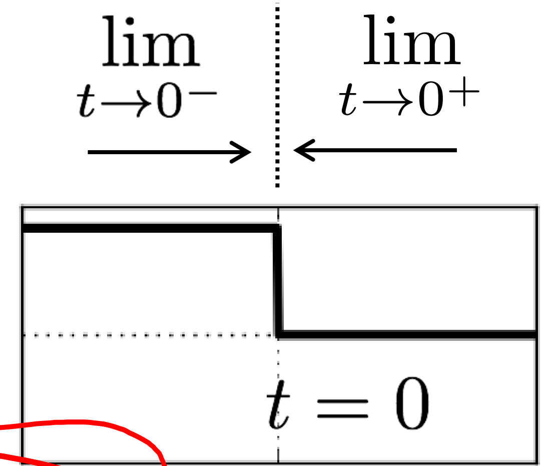
Answer

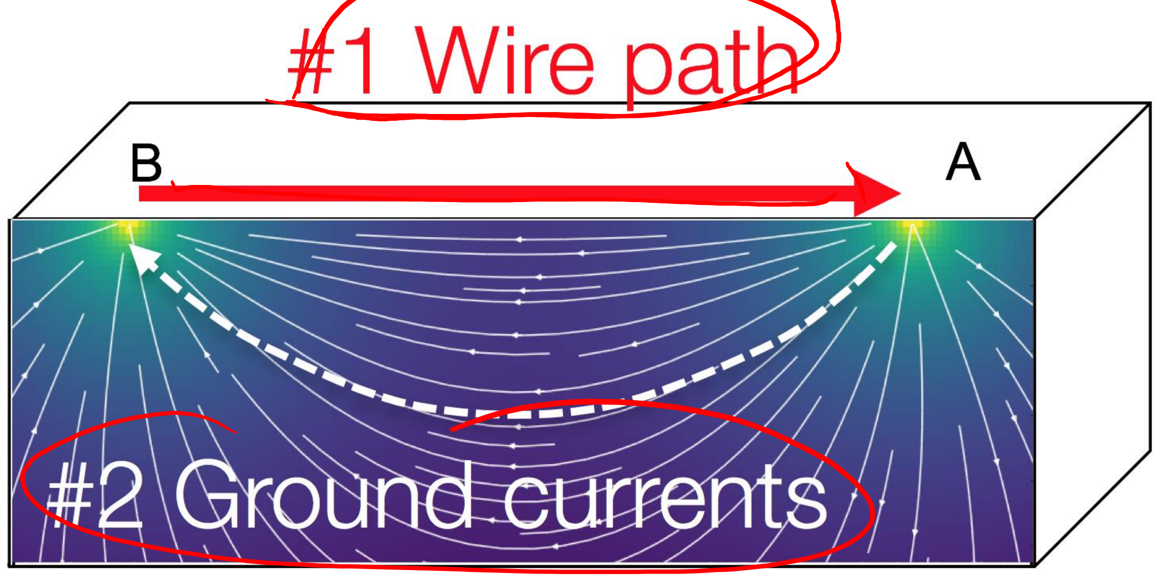
- This is why we are studying EM with grounded sources!

Let us consider TDEM with grounded sources

Currents: Grounded System

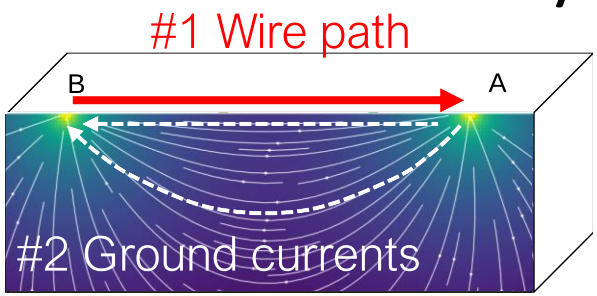
- $t = 0^-$ Steady state
- $t = 0$ Shut off current
- $t = 0^+$ Off-time

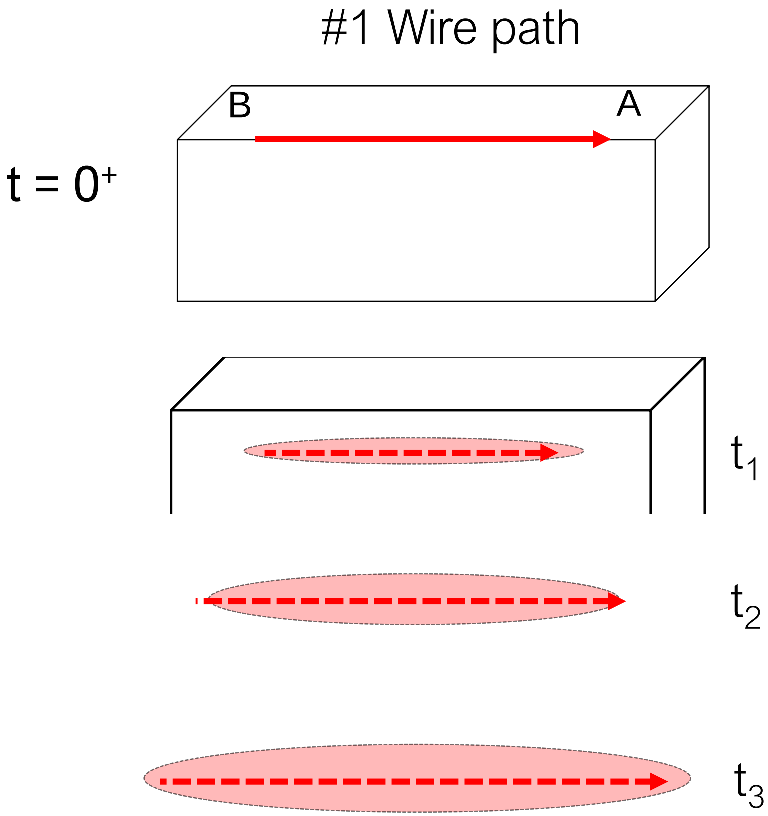




What happens when we shut the system off?

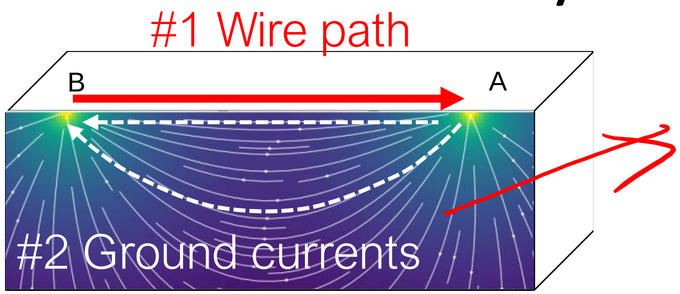
Currents: Grounded System





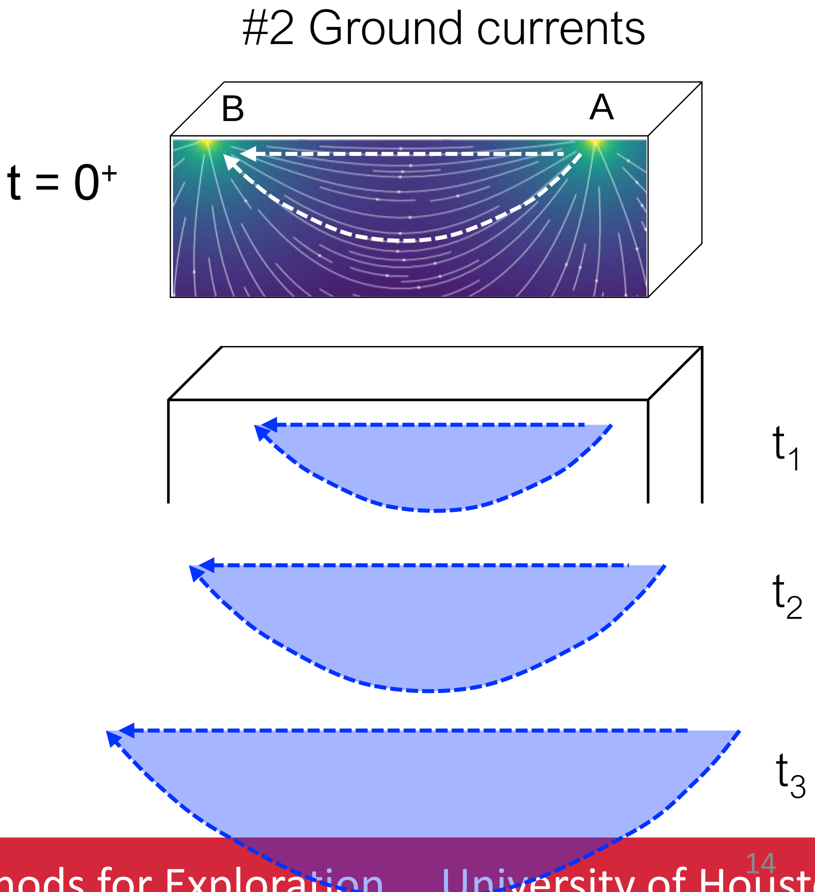
- Immediately after shut off: image current at the surface
- Successive time: currents diffuse downwards and outwards

Currents: Grounded System

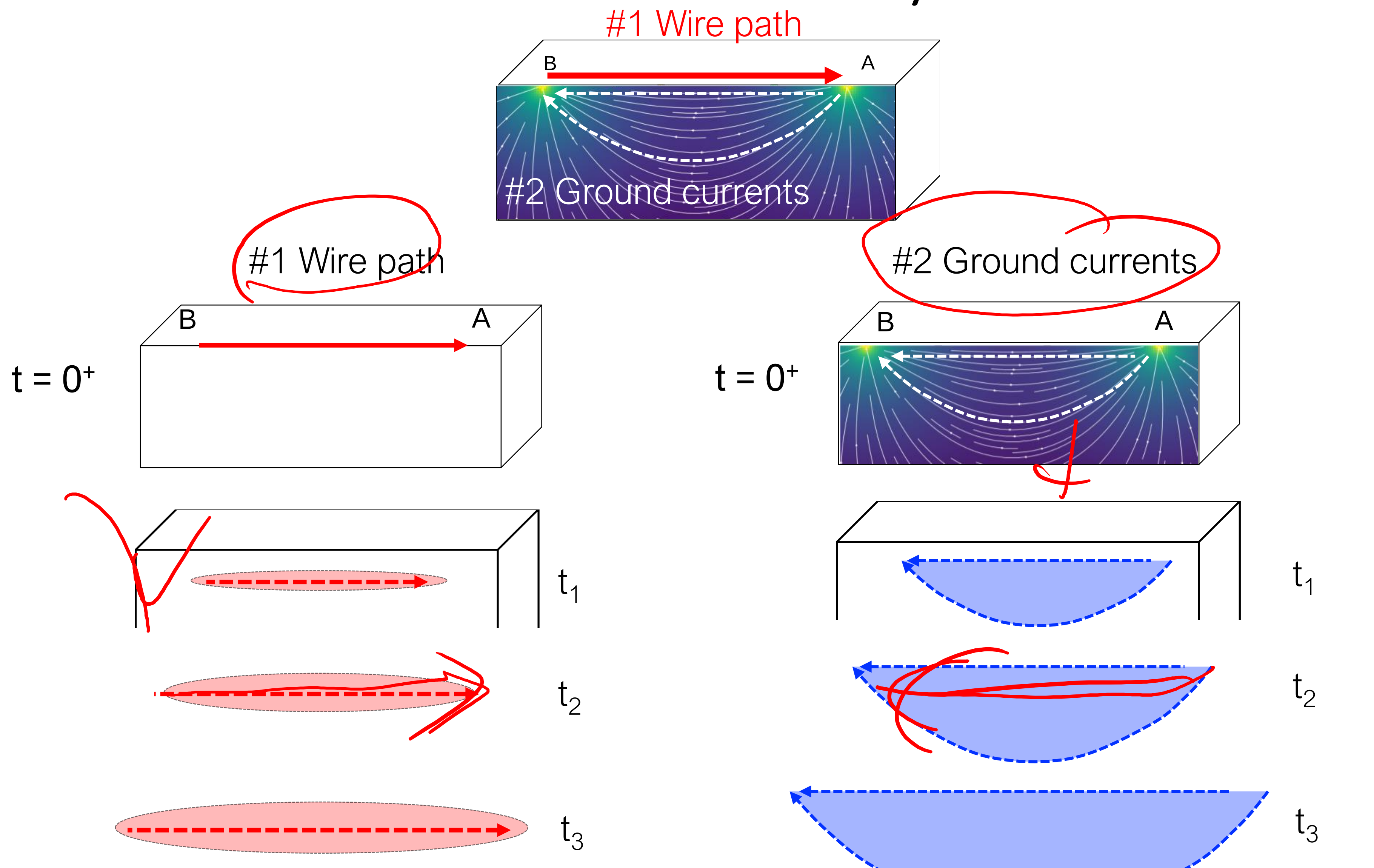


- Immediately after shut off: ground currents are still there

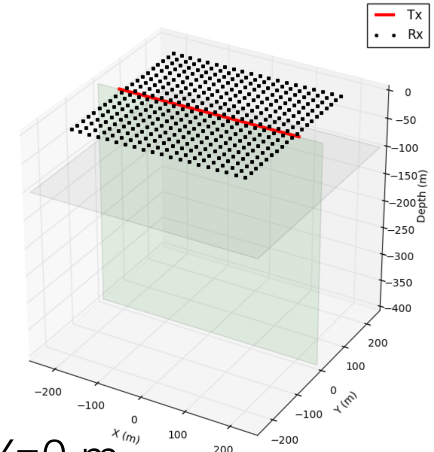
- Successive time: currents diffuse downwards and outwards



Currents: Grounded System

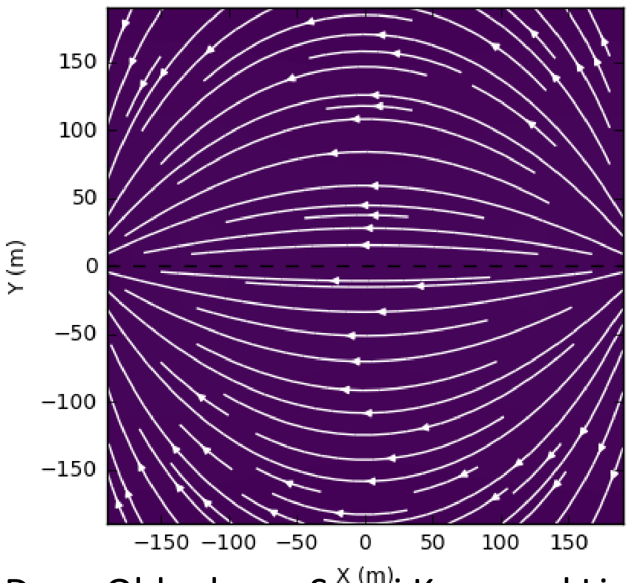


Grounded Source: Halfspace Currents

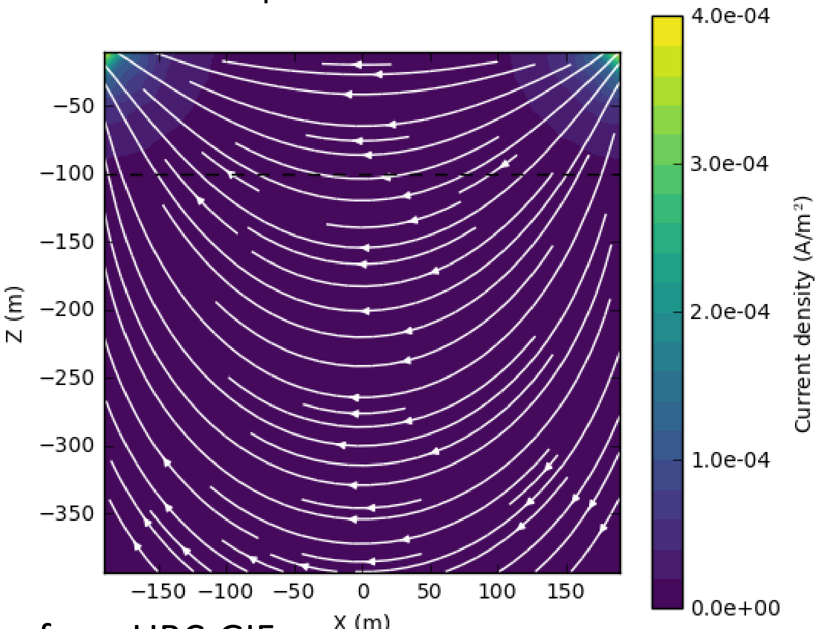


- Parameters:
  - halfspace (0.01 S/m)
  - **t=0$^-$**, steady state

XY plane at Z=-100 m



XZ plane at Y=0 m

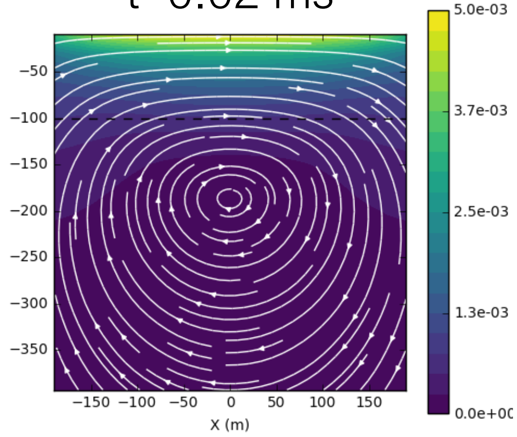


Credit: Doug Oldenburg, Seogi Kang and Linsey Heagy from UBC-GIF

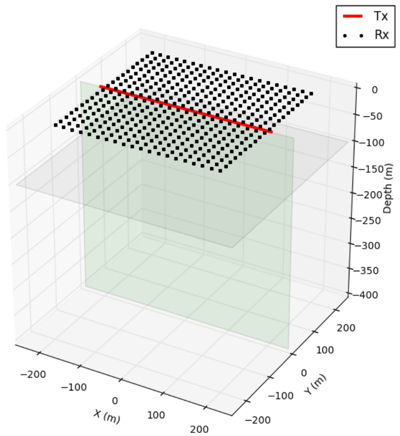
Grounded Source: Halfspace Currents

- Cross section of currents, t = 0.04 to 10 ms

t=0.02 ms



t=0.04 ms

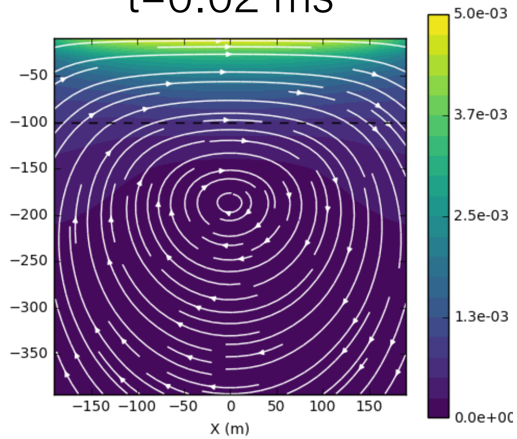


Credit: Doug Oldenburg, Seogi Kang and Linsey Heagy from UBC-GIF

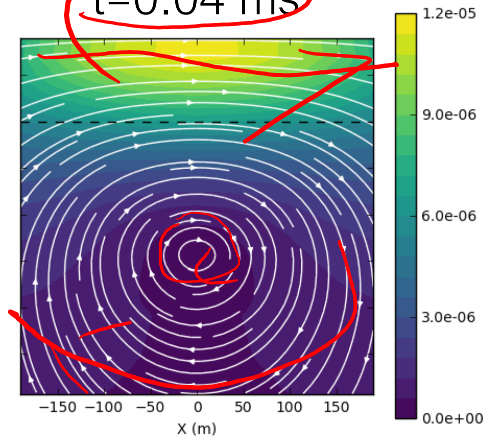
Grounded Source: Halfspace Currents

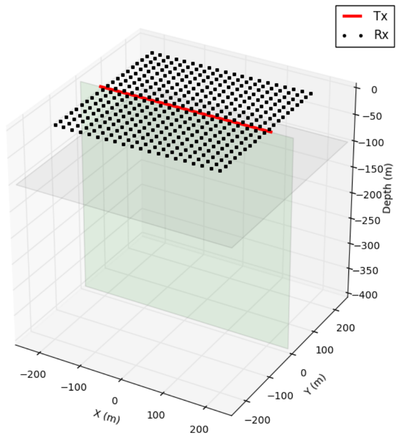
- Cross section of currents, t = 0.04 to 10 ms

t=0.02 ms



t=0.04 ms





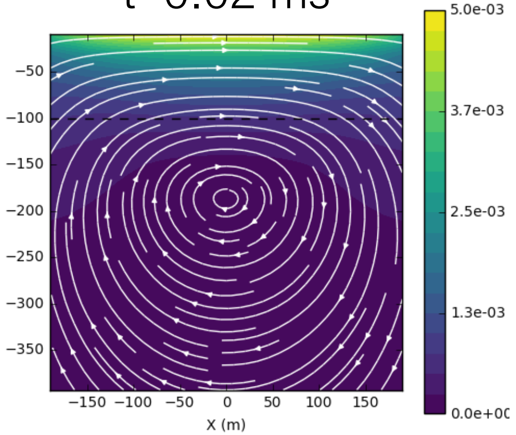
t=0.1 ms

Credit: Doug Oldenburg, Seogi Kang and Linsey Heagy from UBC-GIF

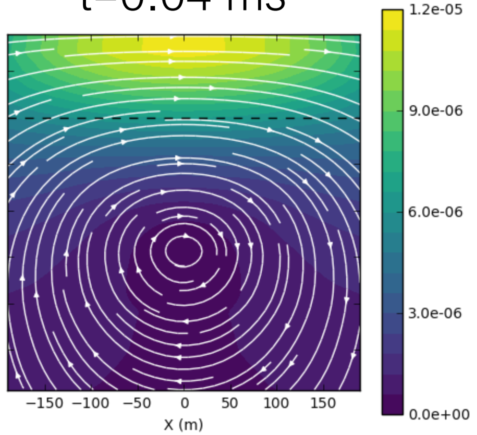
Grounded Source: Halfspace Currents

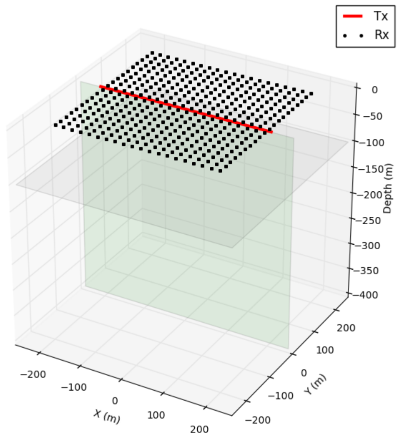
- Cross section of currents, t = 0.04 to 10 ms

t=0.02 ms

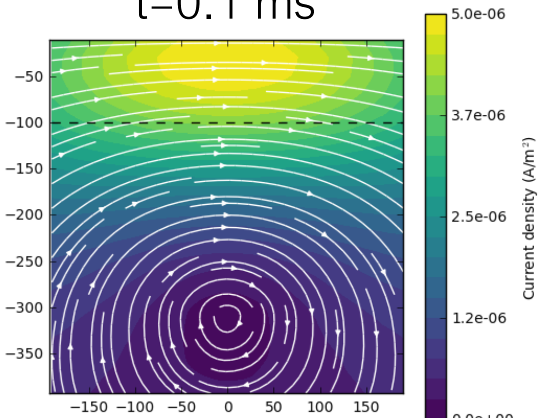


t=0.04 ms





t=0.1 ms



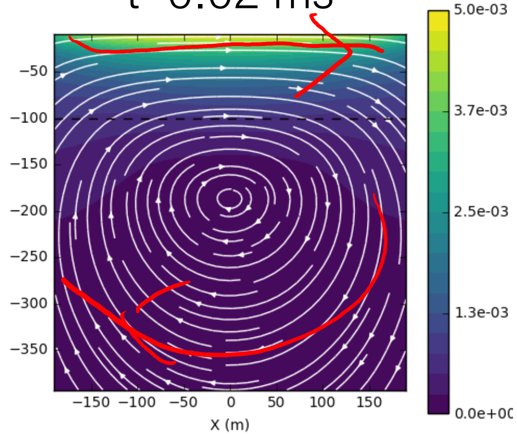
t=1 ms

Credit: Doug Oldenburg, Seogi Kang and Linsey Heagy from UBC-GIF

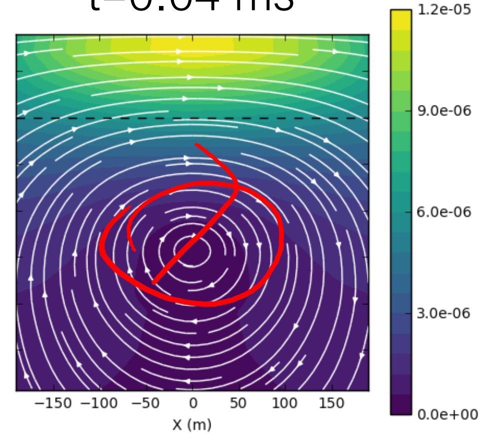
Grounded Source: Halfspace Currents

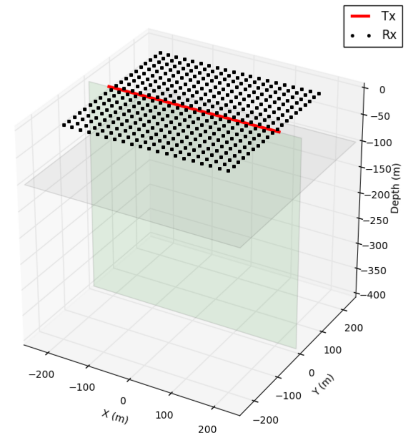
- Cross section of currents, t = 0.04 to 10 ms

t=0.02 ms

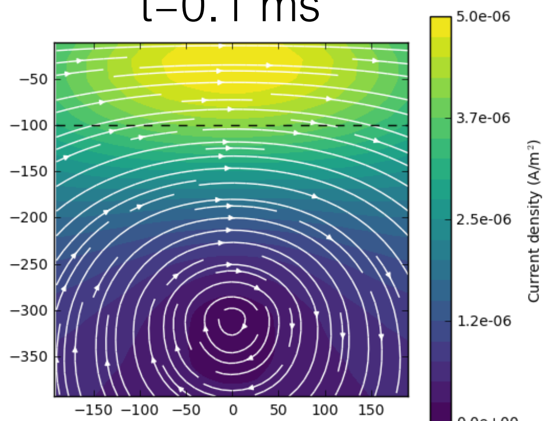


t=0.04 ms

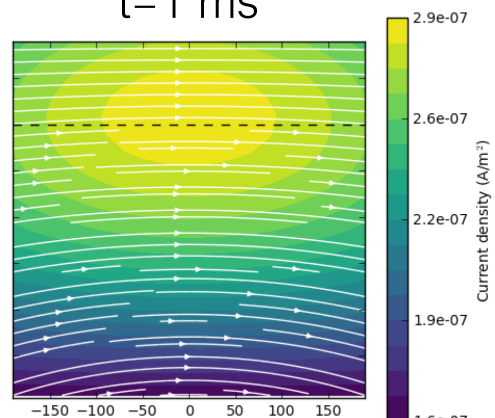




t=0.1 ms



t=1 ms

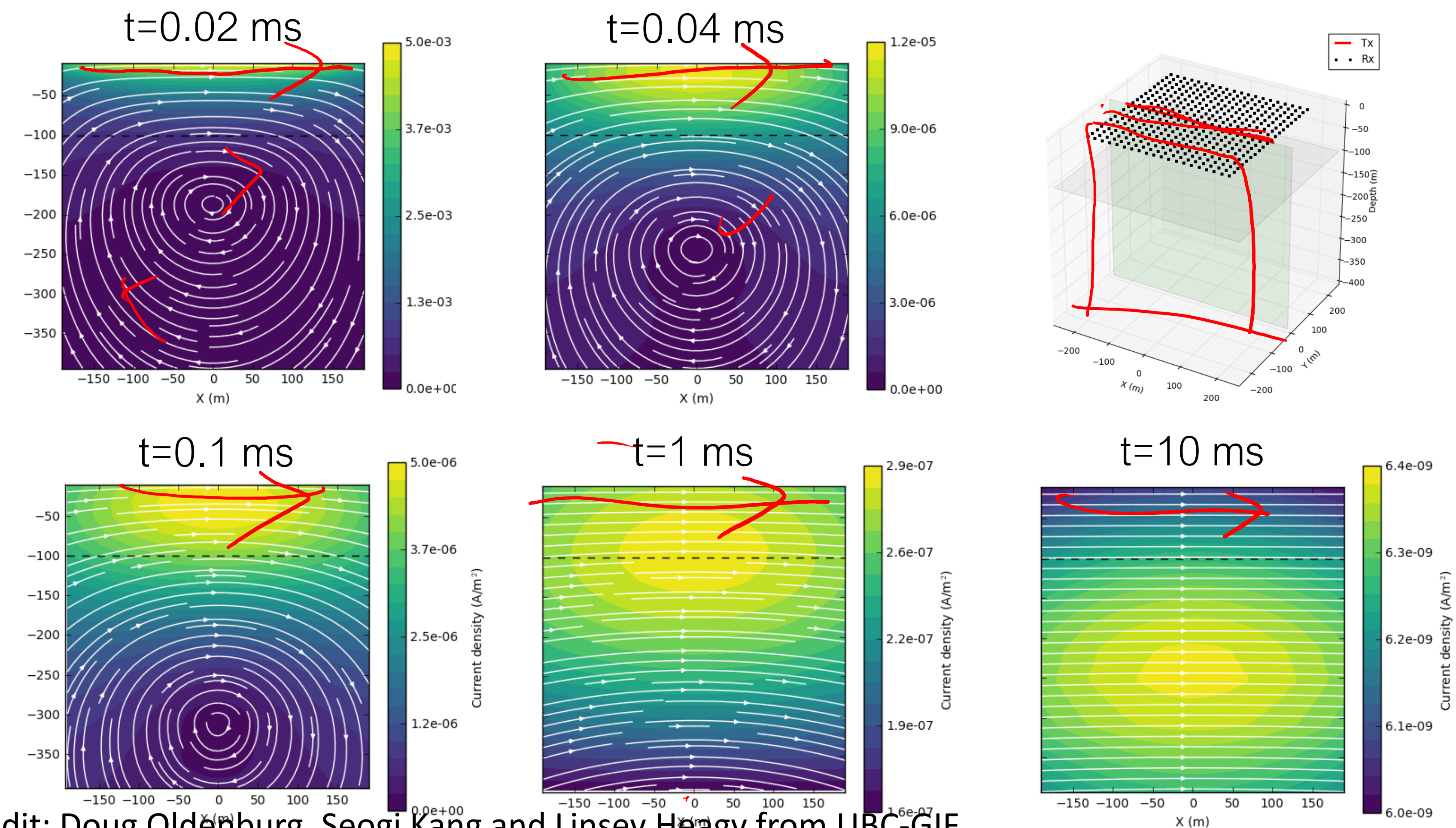


t=10 ms

Credit: Doug Oldenburg, Seogi Kang and Linsey Heagy from UBC-GIF

Grounded Source: Halfspace Currents

- Cross section of currents, t = 0.04 to 10 ms

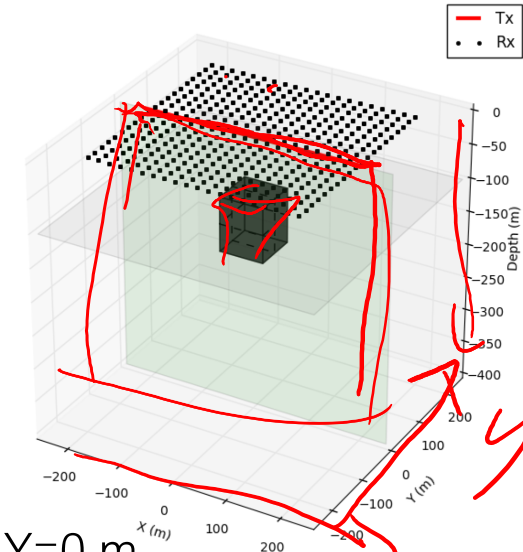


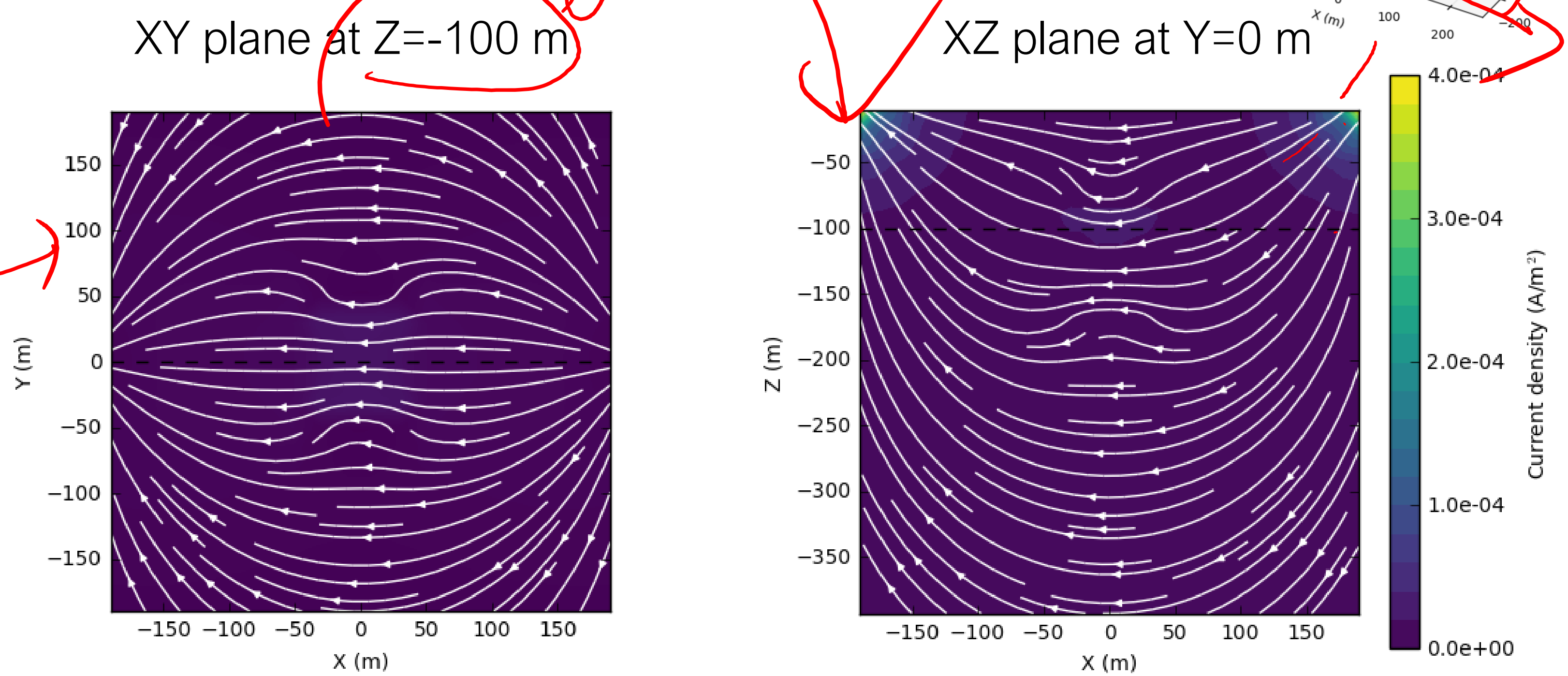
Credit: Doug Oldenburg, Seogi Kang and Linsey Heagy from UBC-GIF

Grounded source EM: with a target

Conductor: currents

- Grounded wire
  - A conductor (1S/m) in a halfspace (0.01 S/m)
  - t=0$^-$, steady state

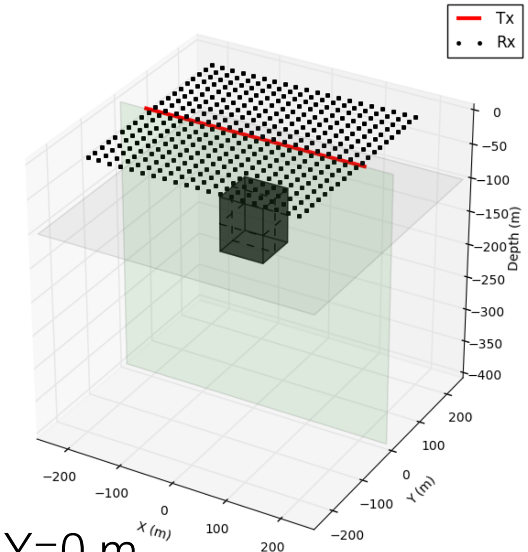




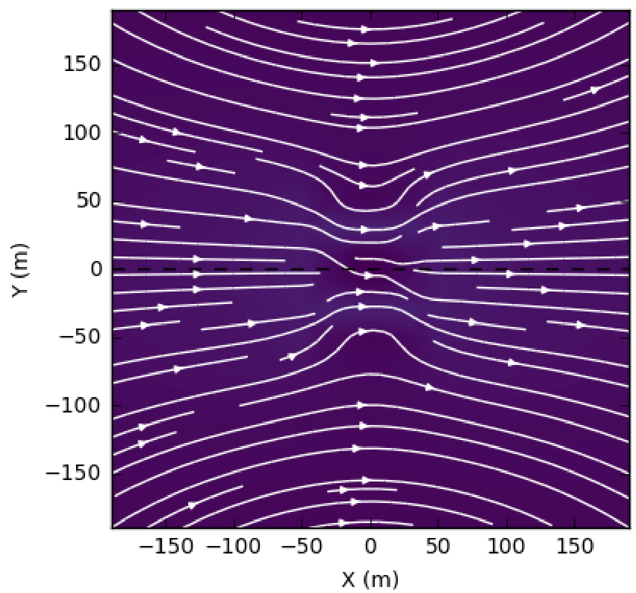
Credit: Doug Oldenburg, Seogi Kang and Linsey Heagy from UBC-GIF

Conductor: currents

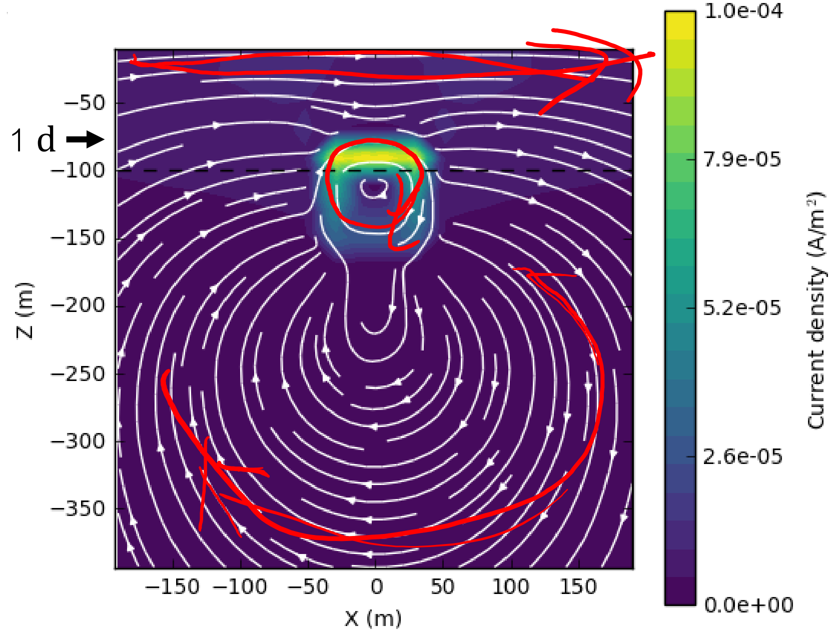
- Grounded wire
  - A conductor (1S/m) in a halfspace (0.01 S/m)
  - **0.04** ms, d = 80 m



XY plane at Z=-100 m

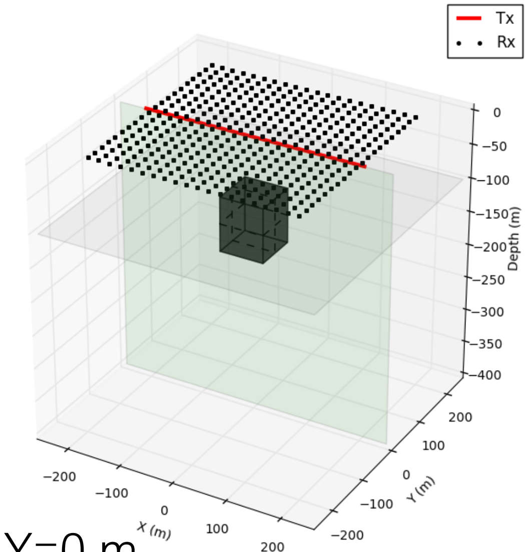


XZ plane at Y=0 m



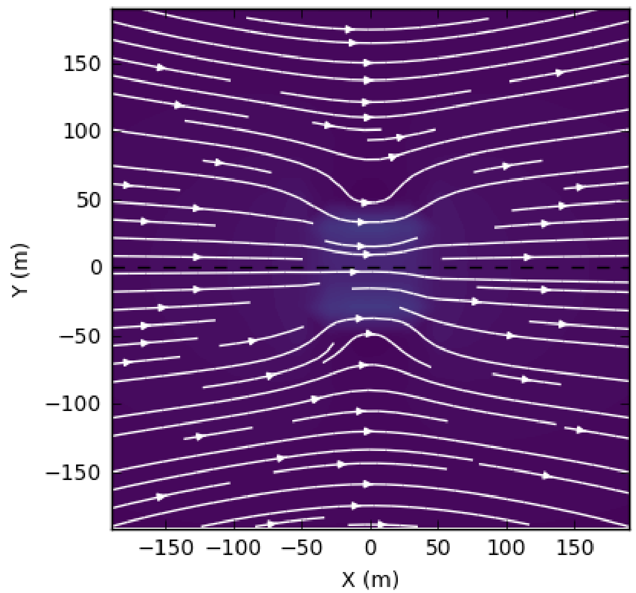
Credit: Doug Oldenburg, Seogi Kang and Linsey Heagy from UBC-GIF

Conductor: currents

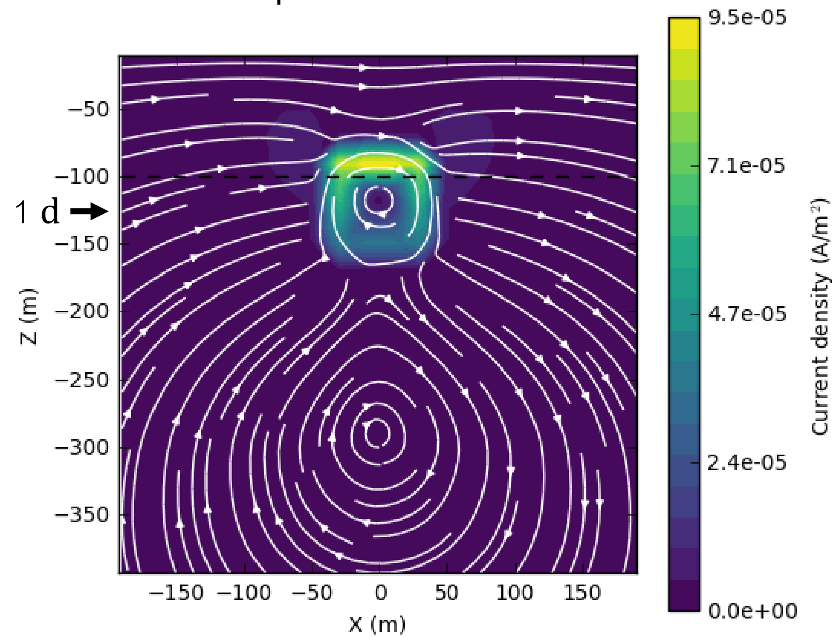


- Grounded wire
  - A conductor (1S/m) in a halfspace (0.01 S/m)
  - **0.1** ms, d = 126 m

XY plane at Z=-100 m



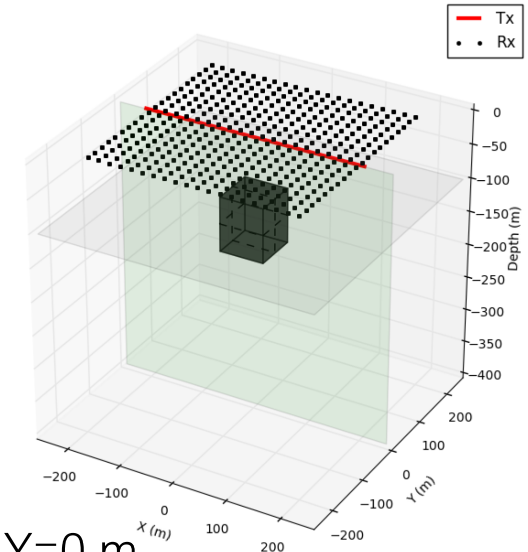
XZ plane at Y=0 m

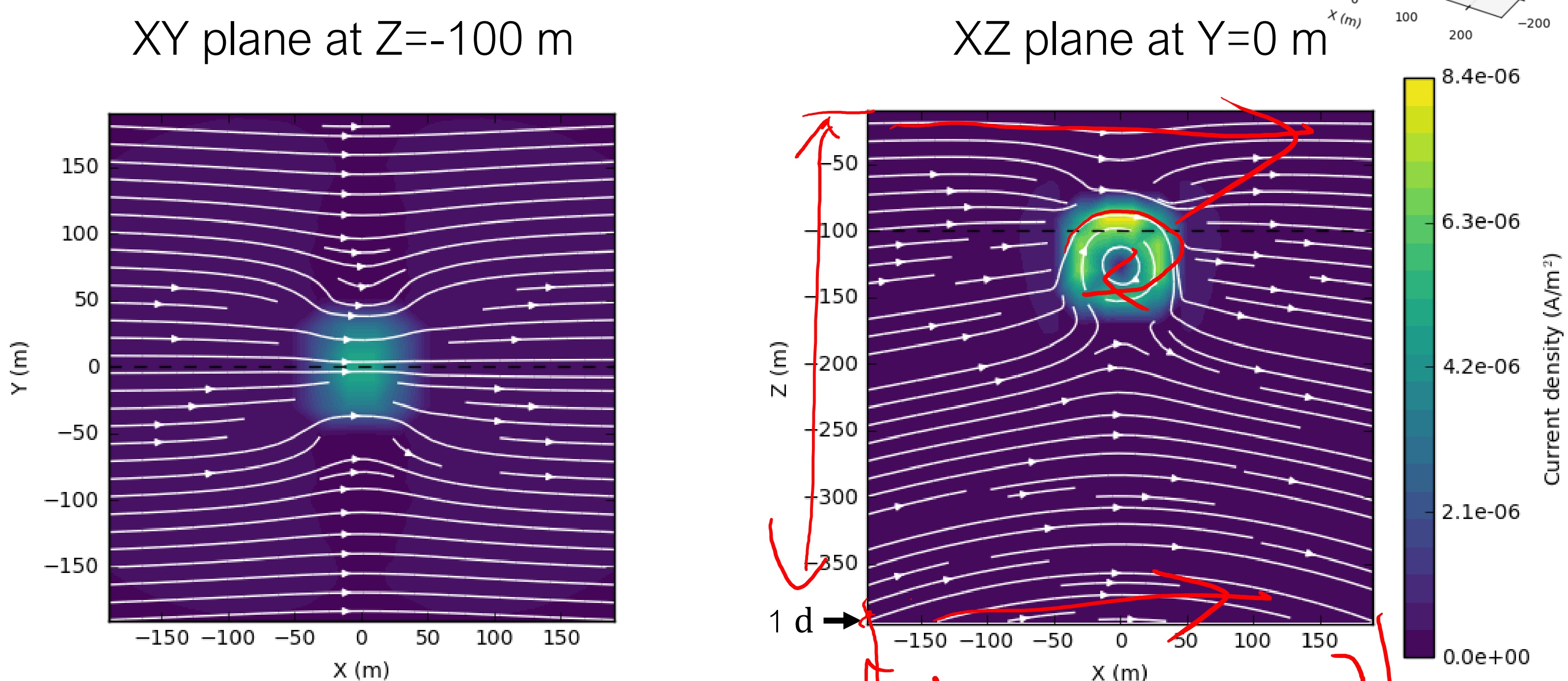


Credit: Doug Oldenburg, Seogi Kang and Linsey Heagy from UBC-GIF

Conductor: currents

- Grounded wire
  - A conductor (1S/m) in a halfspace (0.01 S/m)
  - 1 ms, d = 400 m

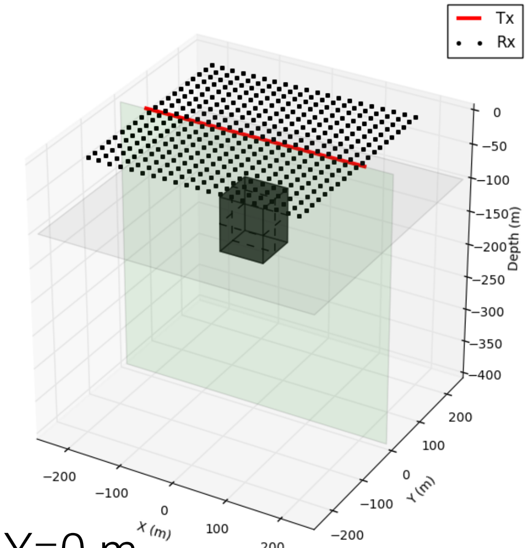




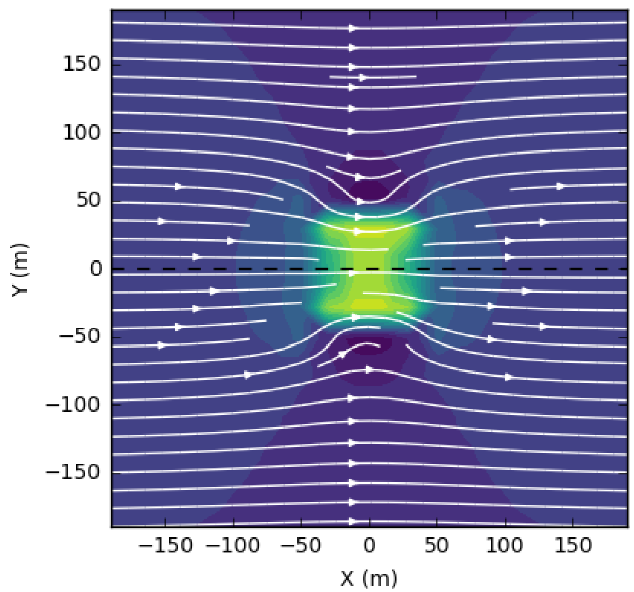
Credit: Doug Oldenburg, Seogi Kang and Linsey Heagy from UBC-GIF

Conductor: currents

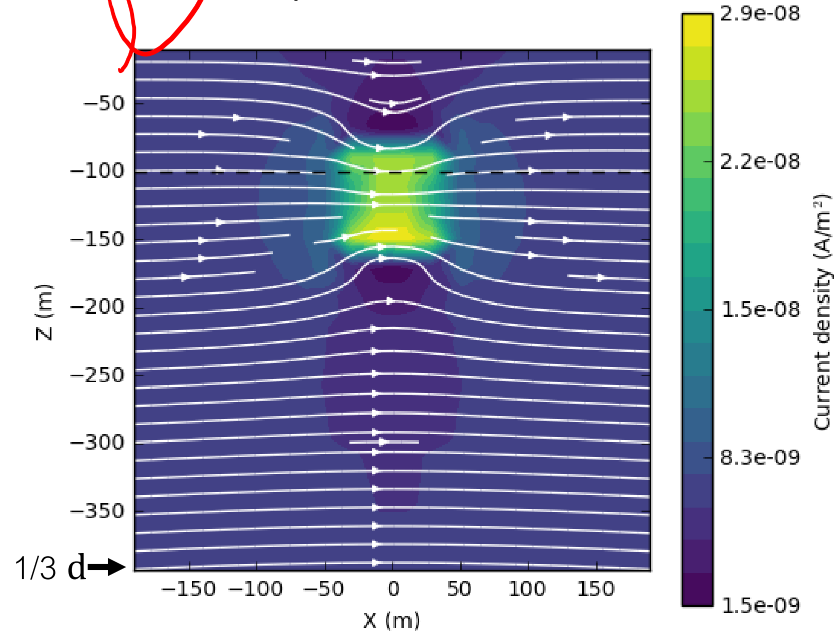
- Grounded wire
  - A conductor (1S/m) in a halfspace (0.01 S/m)
  - **10** ms, d = 1270 m



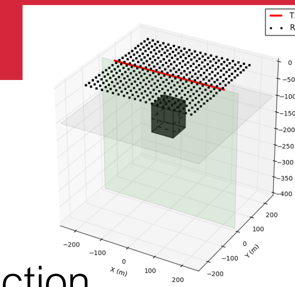
XY plane at Z=-100 m



XZ plane at Y=0 m



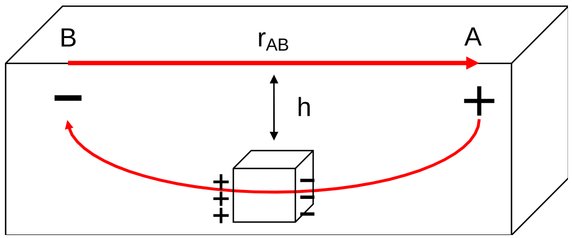
Credit: Doug Oldenburg, Seogi Kang and Linsey Heagy from UBC-GIF



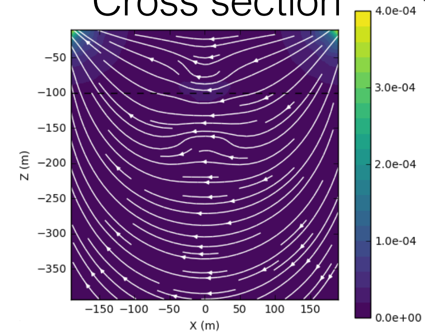
Conductor: currents

Cross section

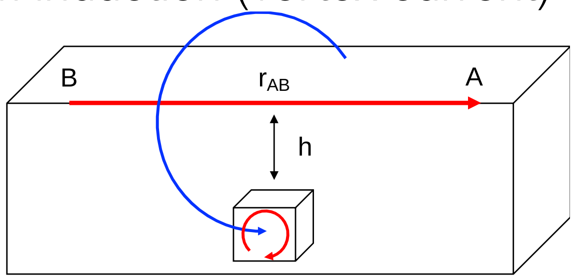
Steady State (galvanic current)



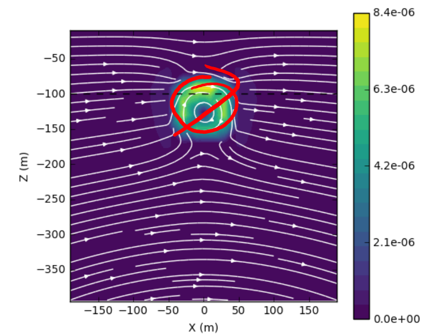
Galvanic current
$t = 0^-$



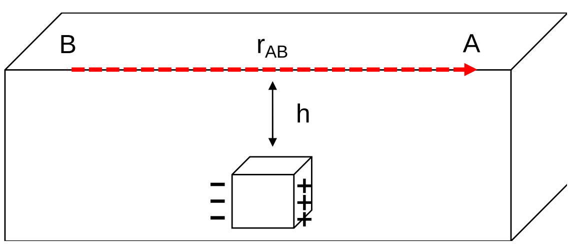
EM induction (vortex current)



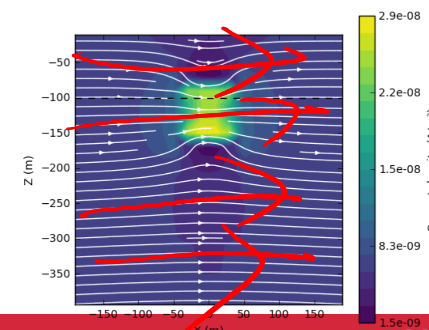
Vortex current
t = 1 ms



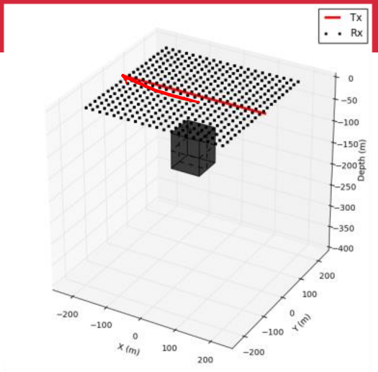
EM induction (galvanic current)

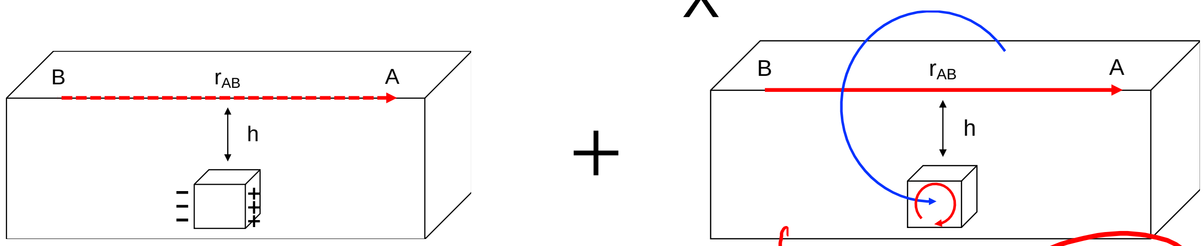


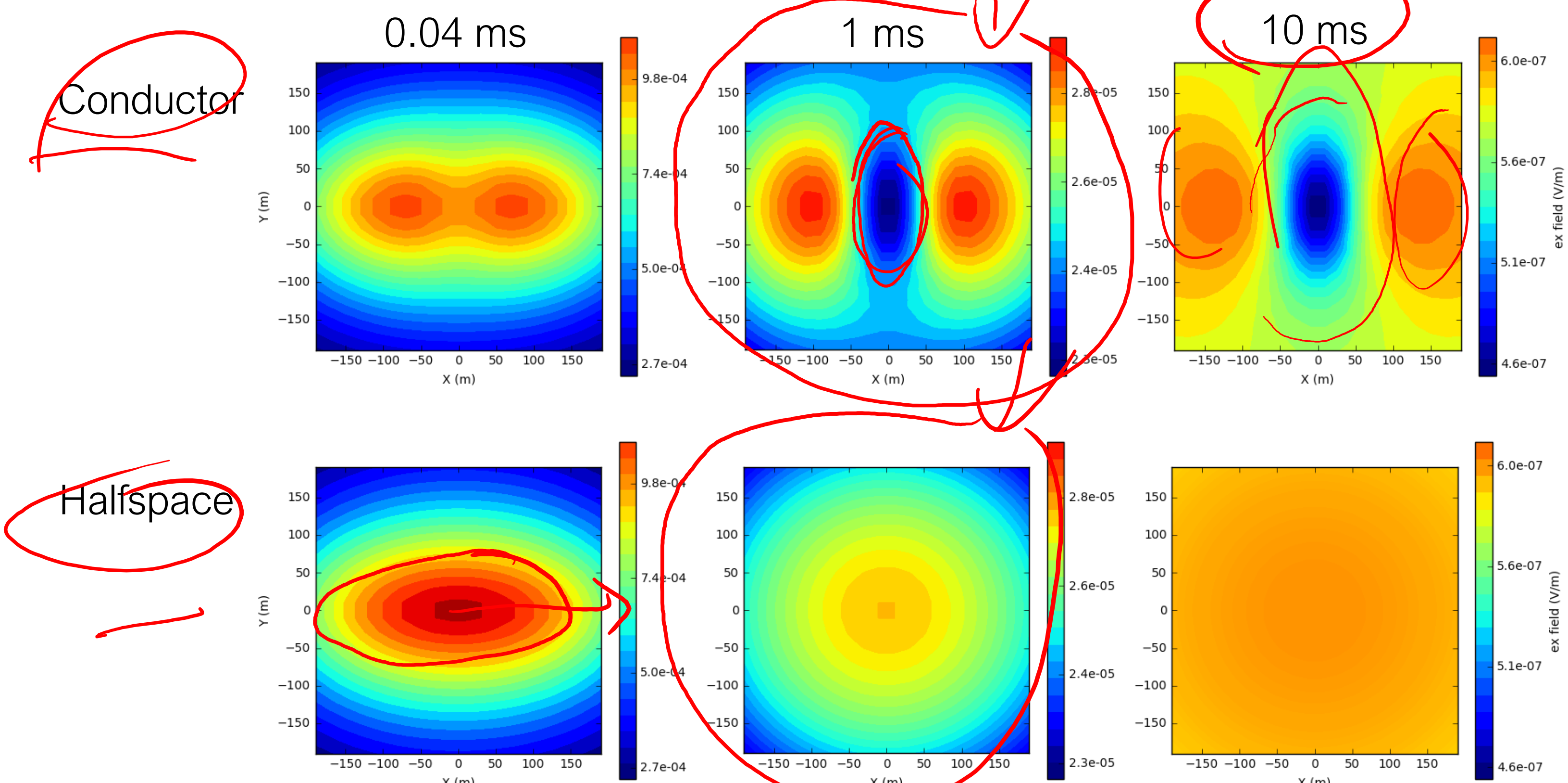
Galvanic current
t = 10 ms



Data: e_x field

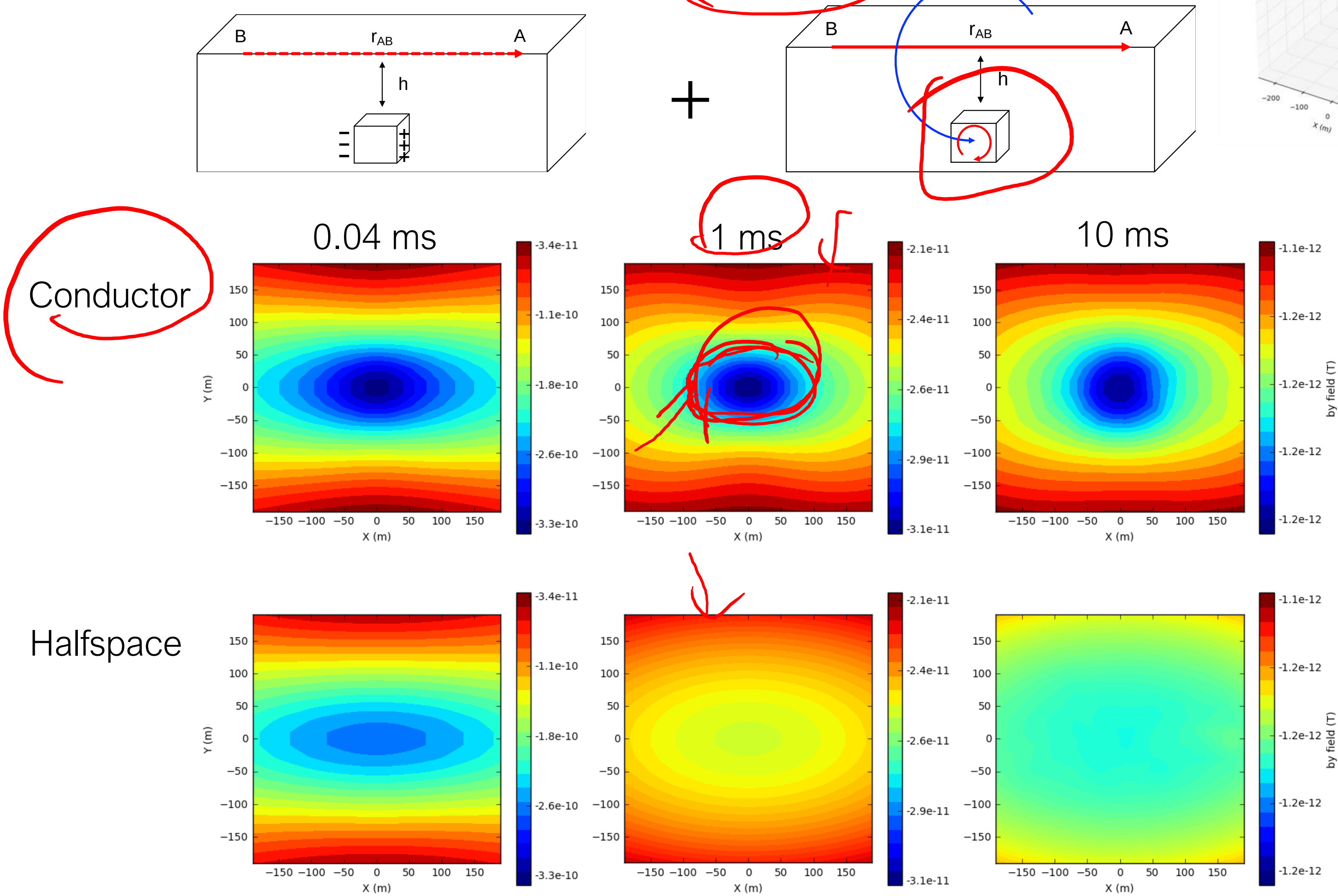


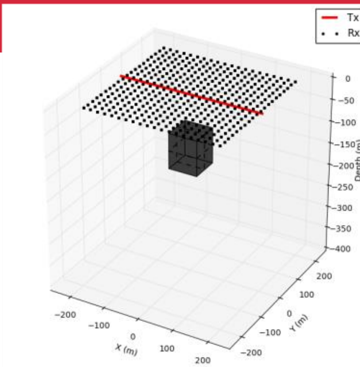




Credit: Doug Oldenburg, Seogi Kang and Linsey Heagy from UBC-GIF

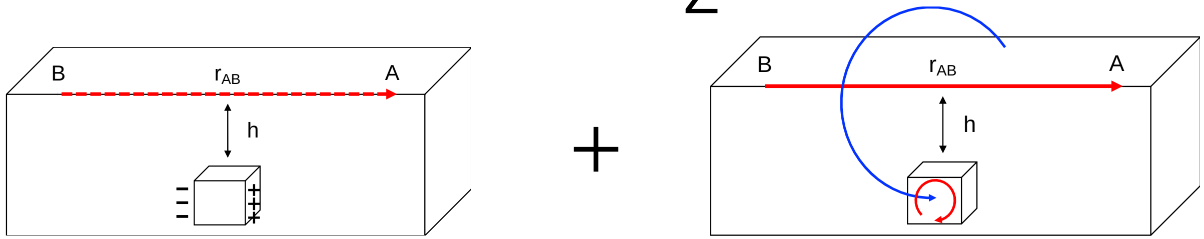
Data: b_y field

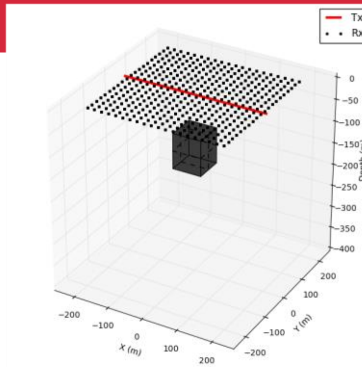




Credit: Doug Oldenburg, Seogi Kang and Linsey Heagy from UBC-GIF

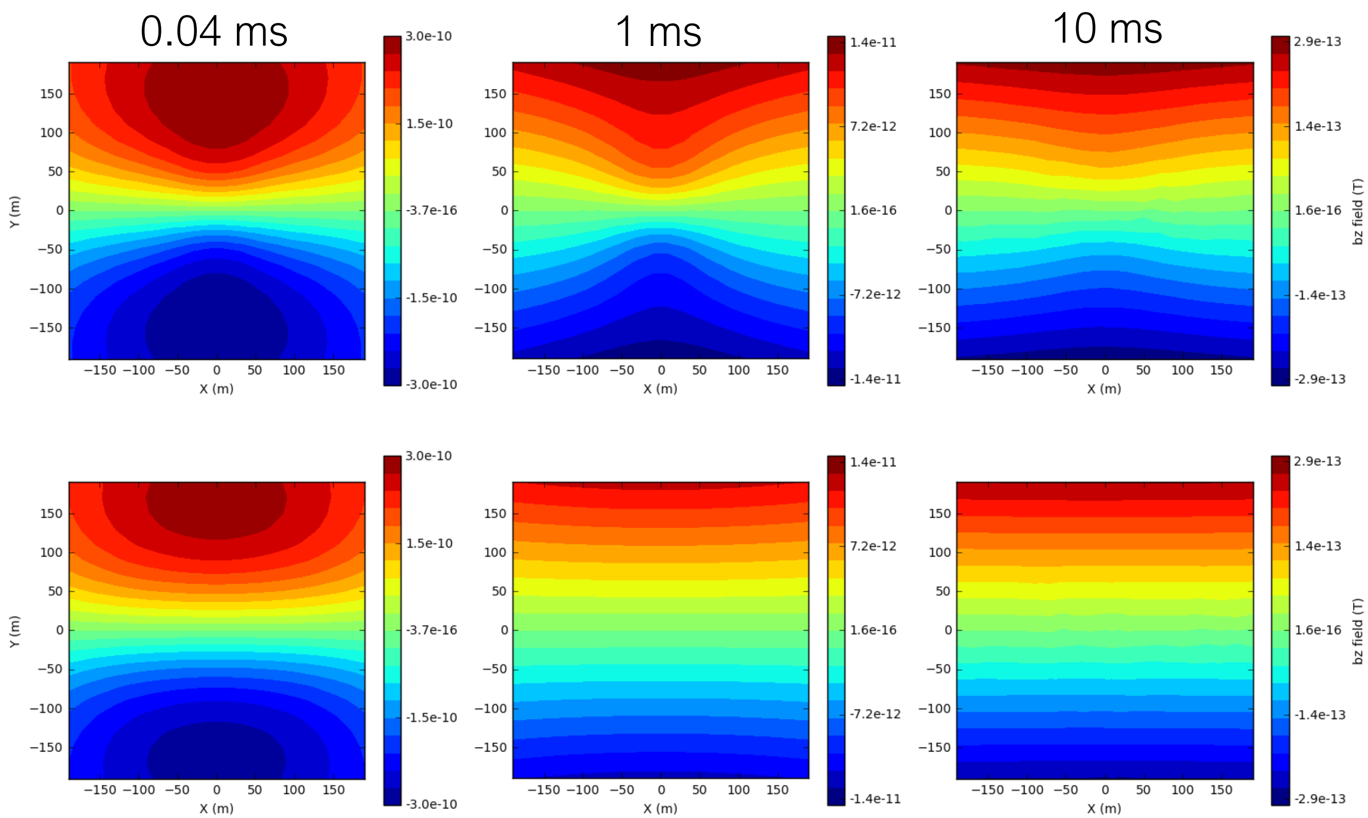
Data: b_z field





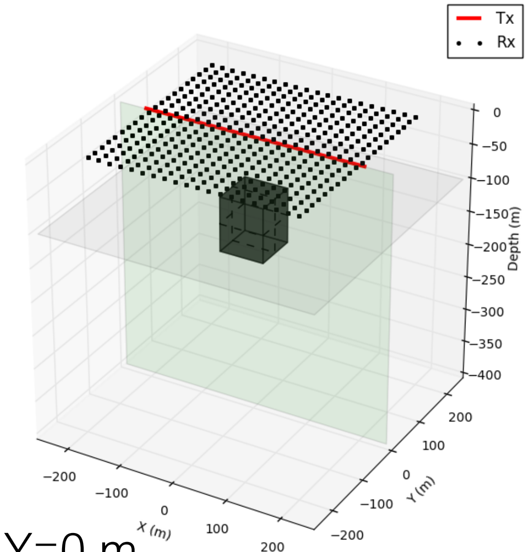
Conductor

Halfspace



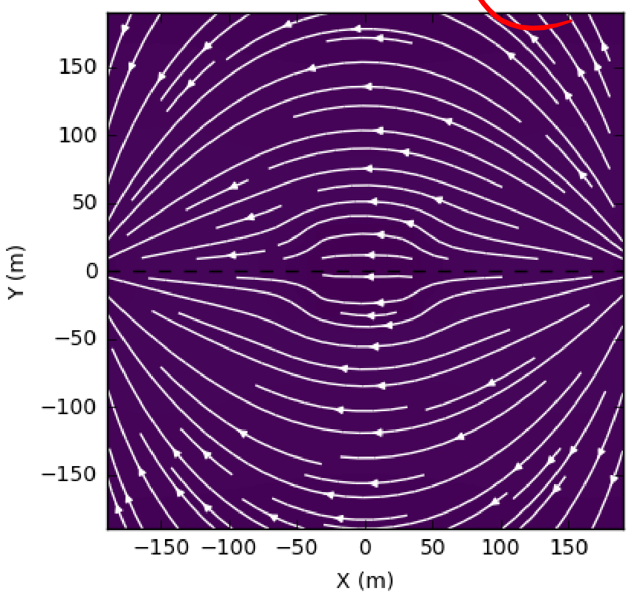
Credit: Doug Oldenburg, Seogi Kang and Linsey Heagy from UBC-GIF

Resistor: currents

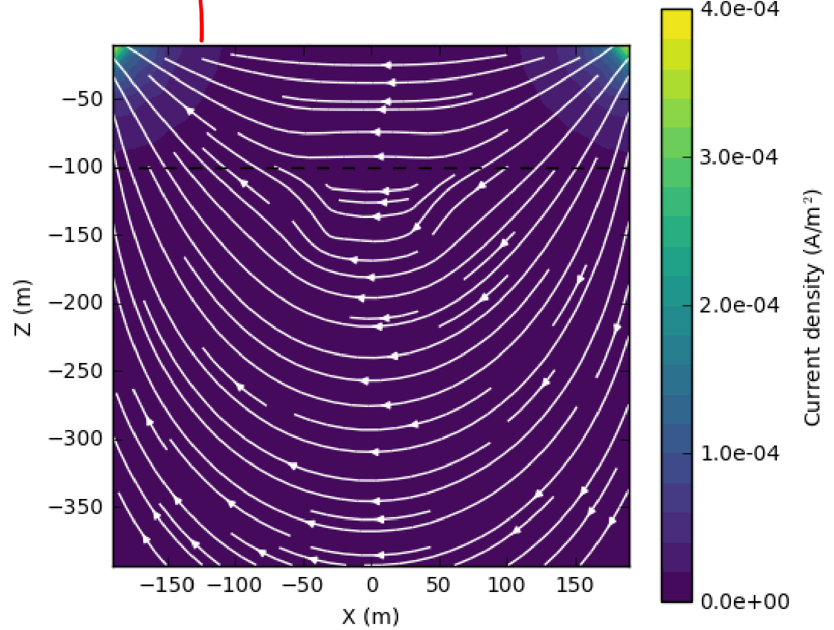


- Grounded wire
  - A resistor (10^{-4} S/m) in a halfspace (0.01 S/m)
  - **t=0⁻**, steady state

XY plane at Z=-100 m

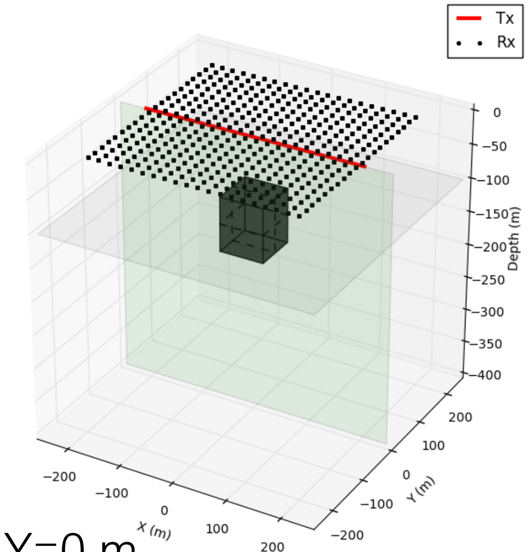


XZ plane at Y=0 m

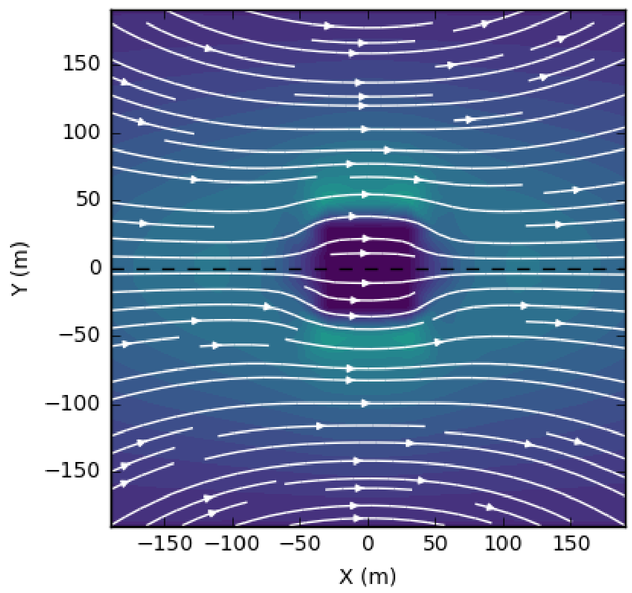


Resistor: currents

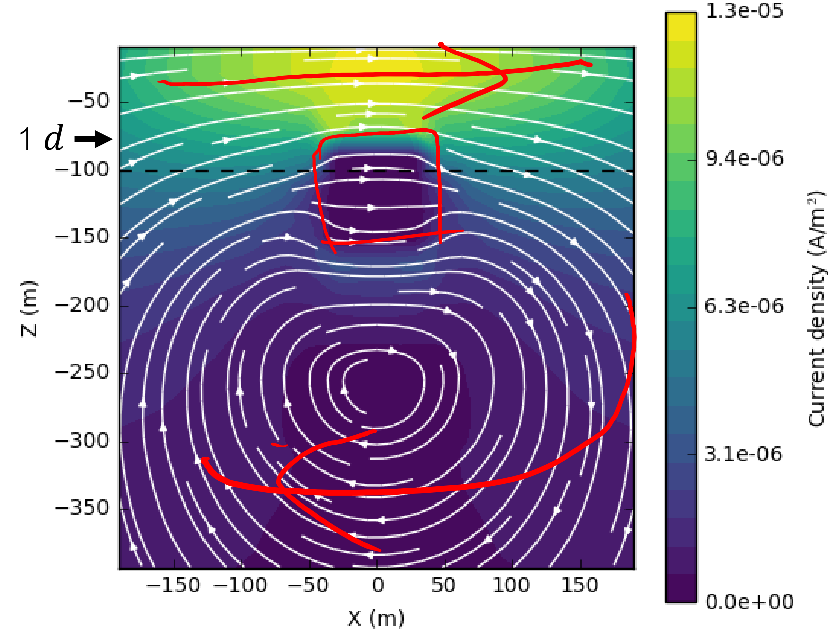
- Grounded wire
  - A resistor (10^{-4} S/m) in a halfspace (0.01 S/m)
  - **0.04** ms, d = 80 m



XY plane at Z=-100 m



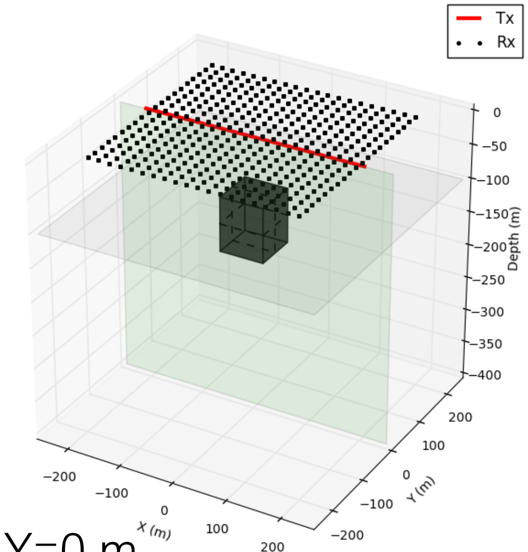
XZ plane at Y=0 m



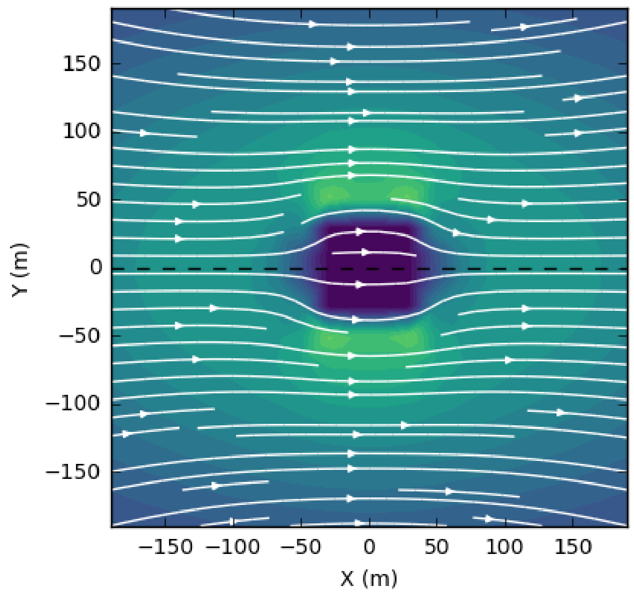
Credit: Doug Oldenburg, Seogi Kang and Linsey Heagy from UBC-GIF

Resistor: currents

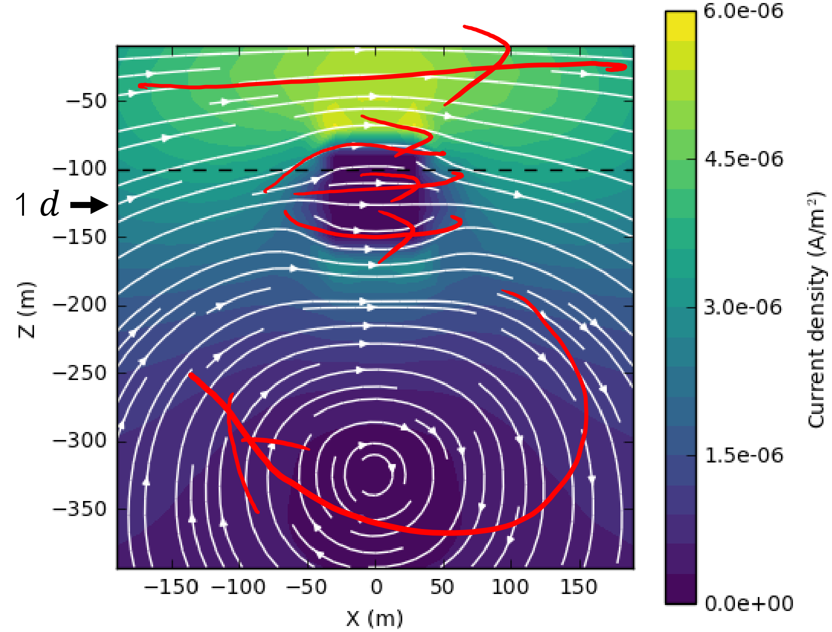
- Grounded wire
  - A resistor (10^{-4} S/m) in a halfspace (0.01 S/m)
  - 0.1 ms, d = 126 m



XY plane at Z=-100 m

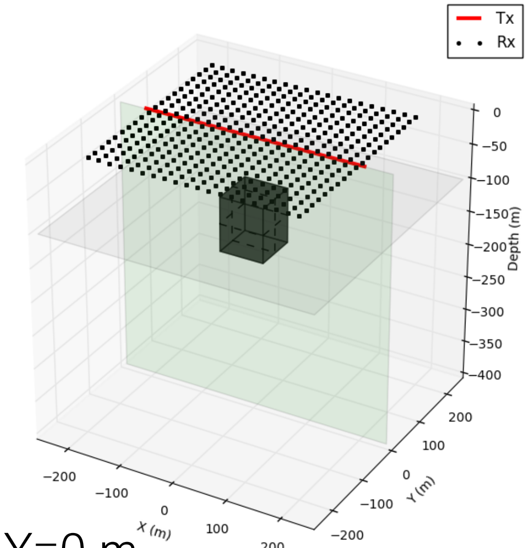


XZ plane at Y=0 m



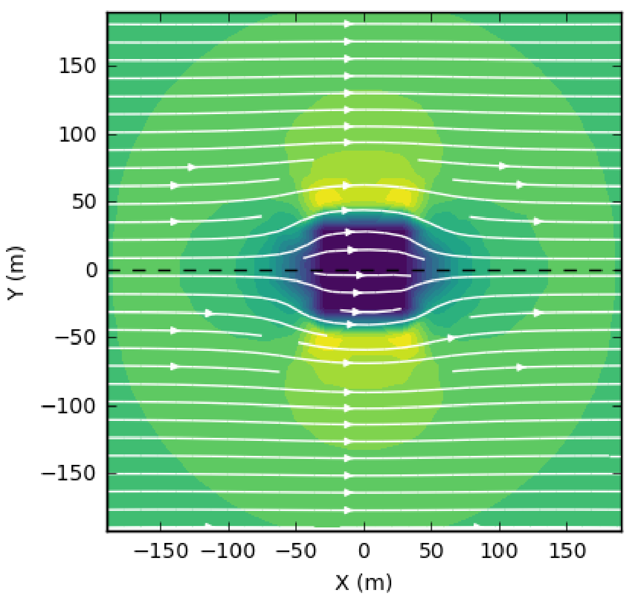
Credit: Doug Oldenburg, Seogi Kang and Linsey Heagy from UBC-GIF

Resistor: currents

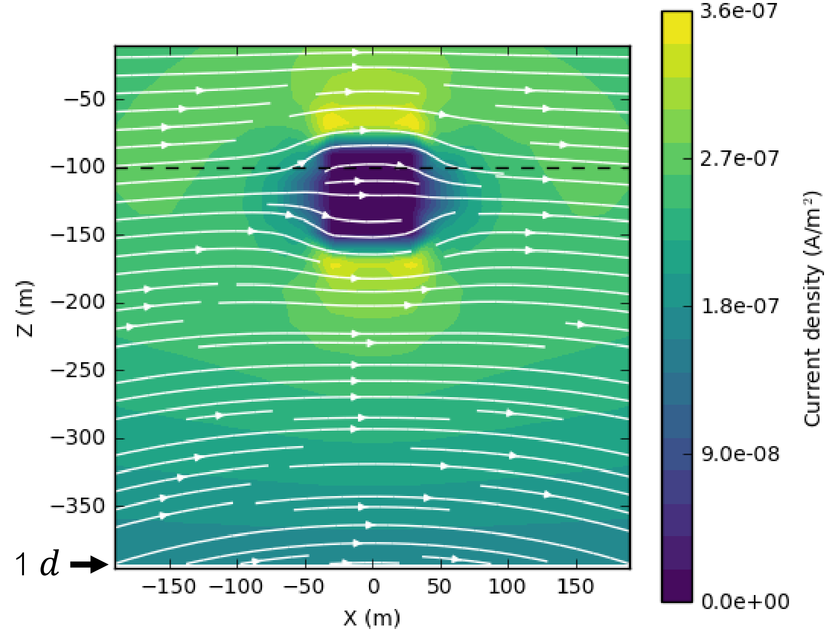


- Grounded wire
  - A resistor (10^{-4} S/m) in a halfspace (0.01 S/m)
  - 1 ms, d = 400 m

XY plane at Z=-100 m



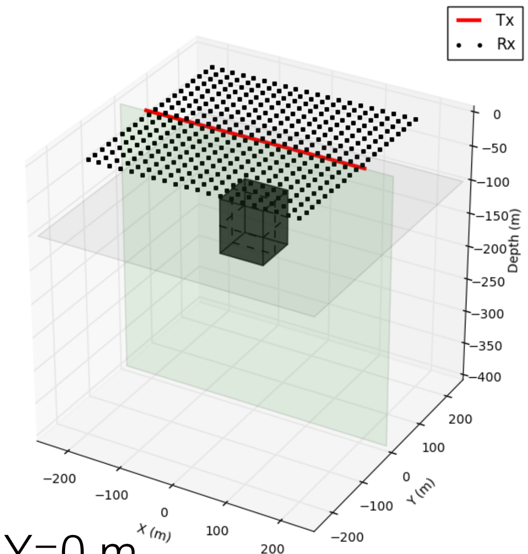
XZ plane at Y=0 m



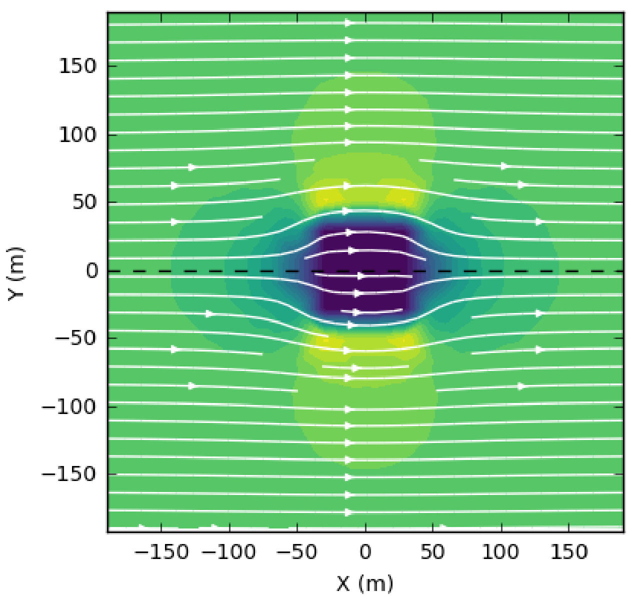
Credit: Doug Oldenburg, Seogi Kang and Linsey Heagy from UBC-GIF

Resistor: currents

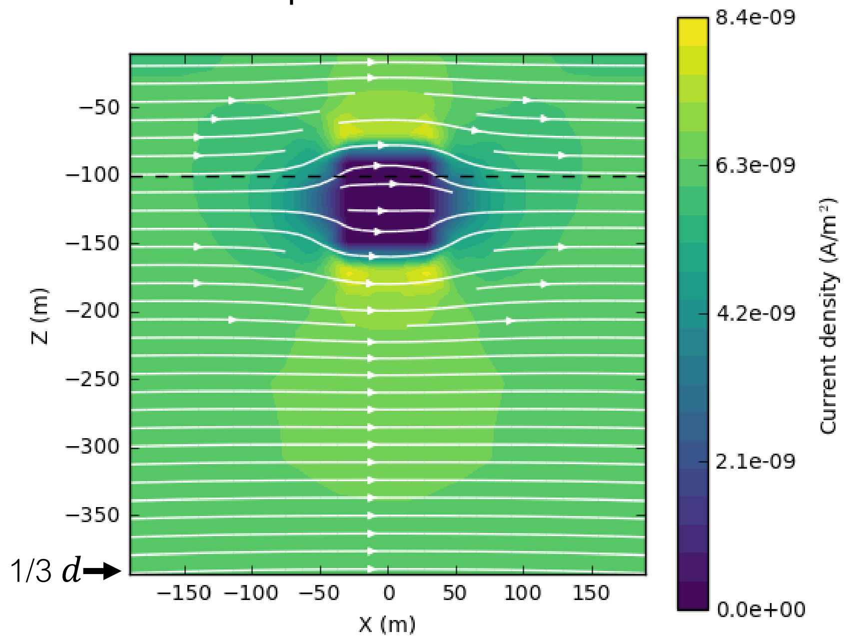
- Grounded wire
  - A resistor (10^{-4} S/m) in a halfspace (0.01 S/m)
  - **10** ms, d = 1270 m



XY plane at Z=-100 m

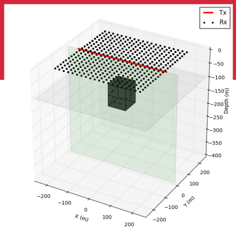


XZ plane at Y=0 m

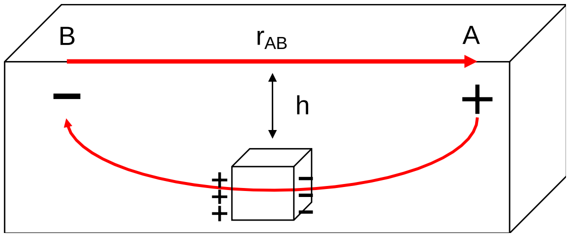


Credit: Doug Oldenburg, Seogi Kang and Linsey Heagy from UBC-GIF

Resistor: currents

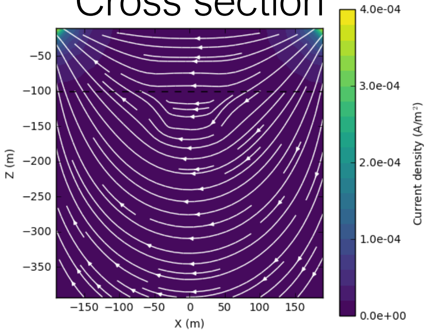


DC (galvanic current)

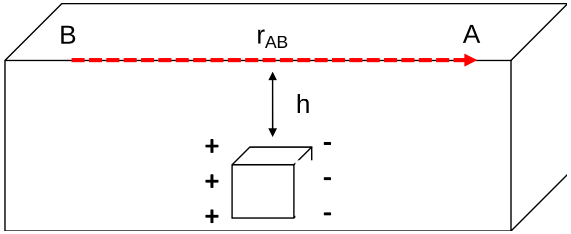


Galvanic current
$t = 0^-$

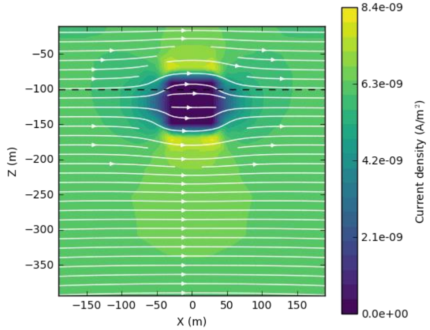
Cross section



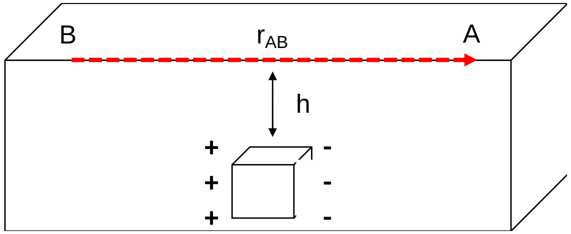
EM induction (galvanic current)



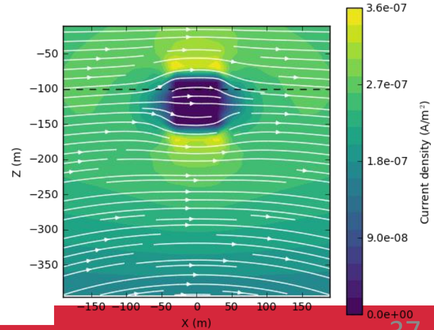
Galvanic current
$t = 1$ ms



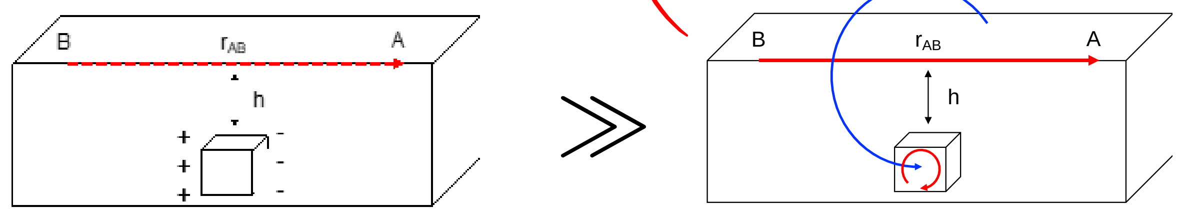
EM induction (galvanic current)

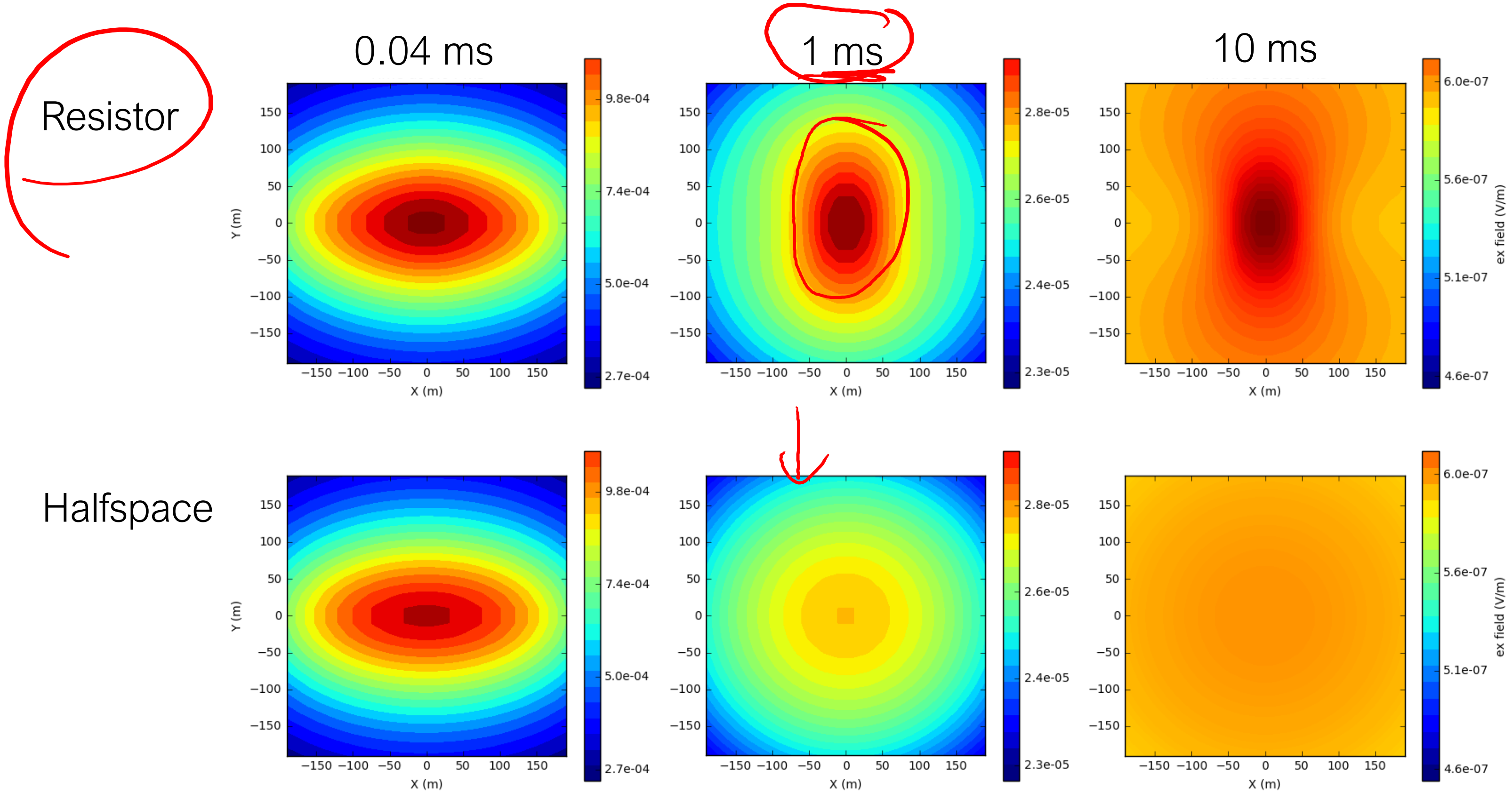


Galvanic current
$t = 10$ ms



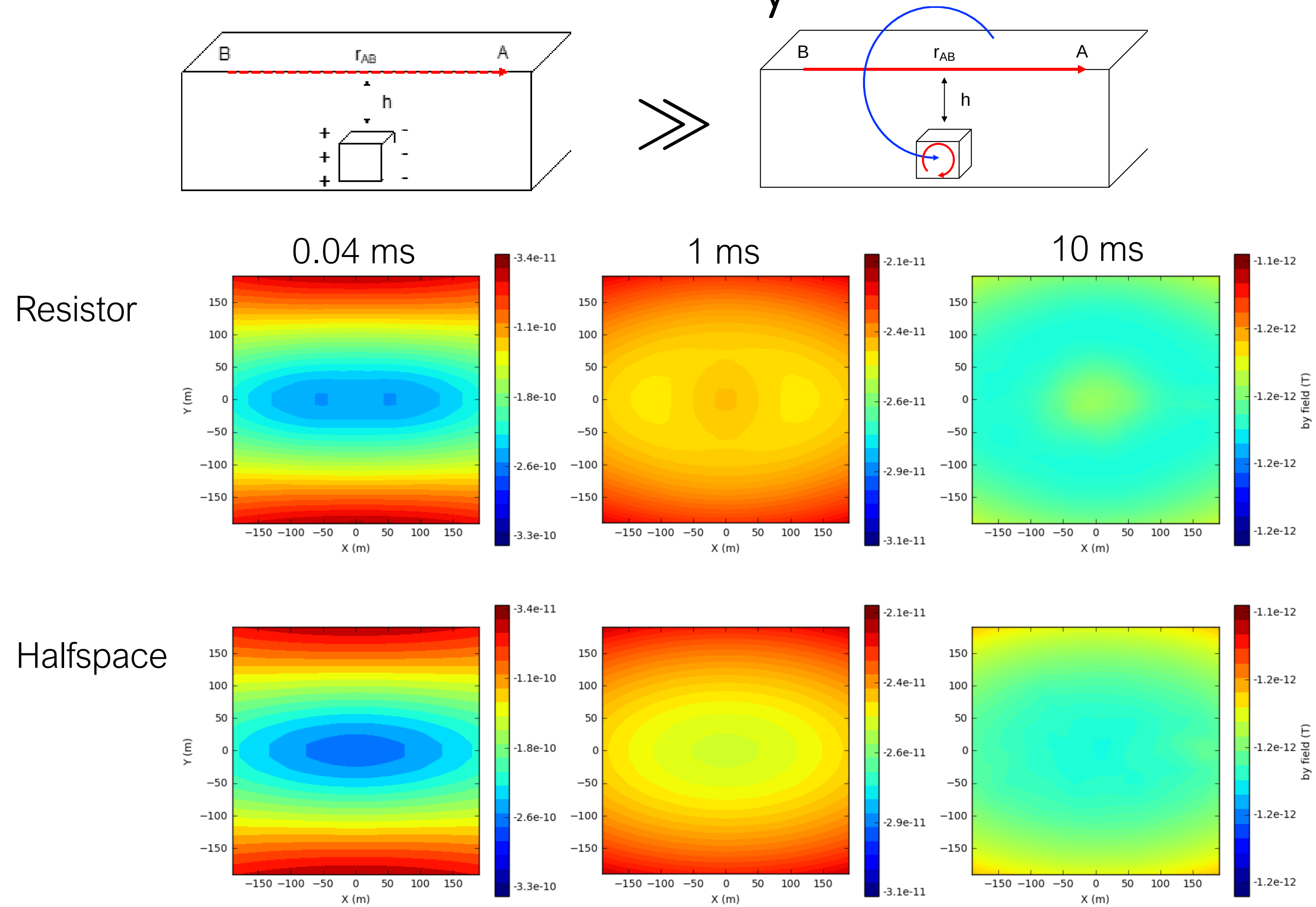
Data: e_x field





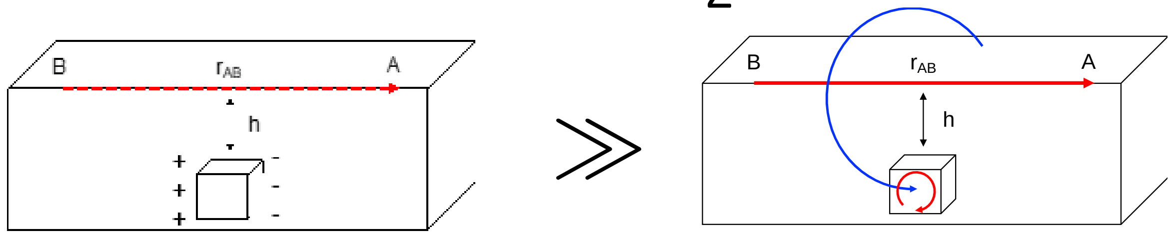
Credit: Doug Oldenburg, Seogi Kang and Linsey Heagy from UBC-GIF

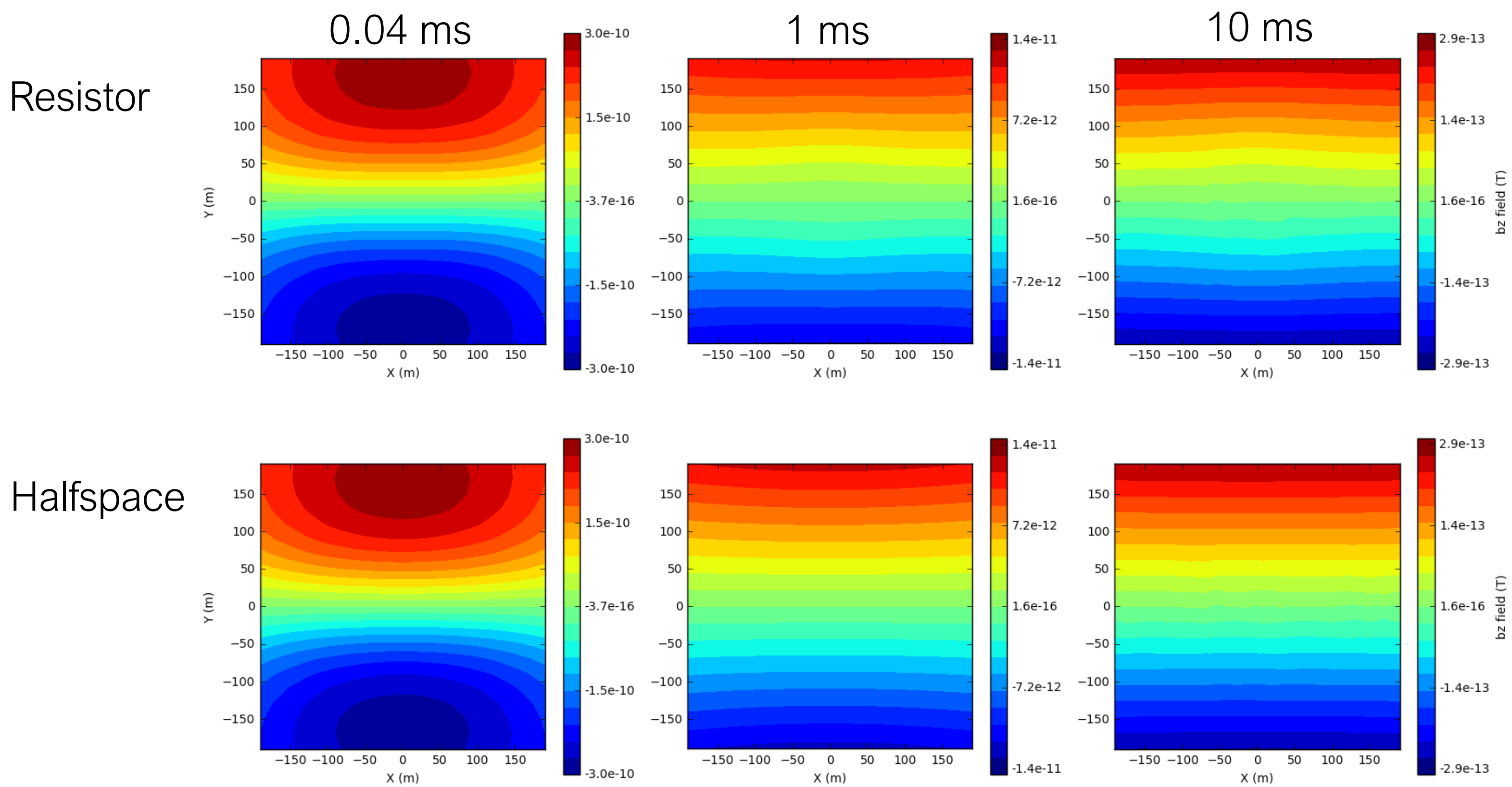
Data: b_y field



Credit: Doug Oldenburg, Seogi Kang and Linsey Heagy from UBC-GIF

Data: b_z field





Credit: Doug Oldenburg, Seogi Kang and Linsey Heagy from UBC-GIF

Data summary

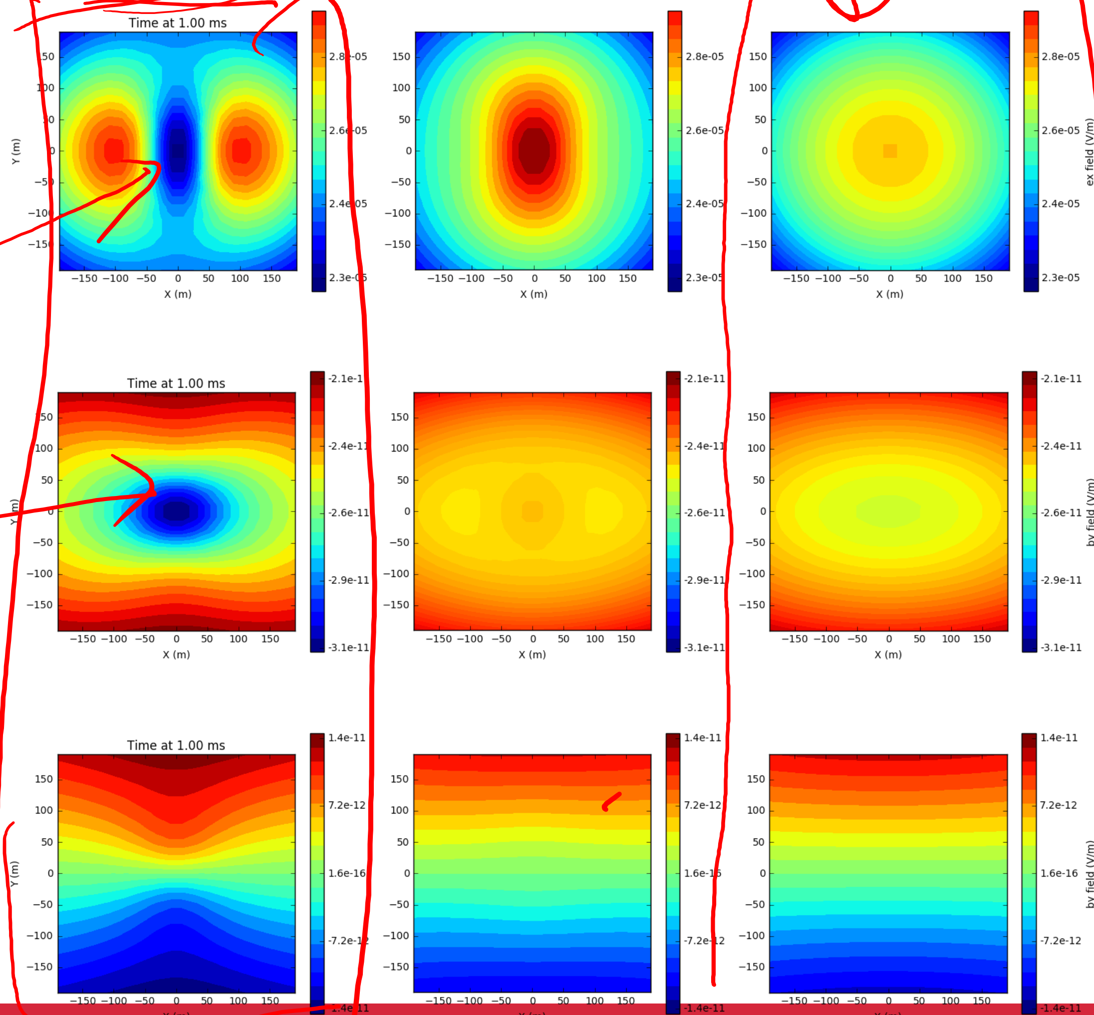
t = 1ms

Conductor | Resistor | Halfspace

e_x

b_y

b_z



Summary

- Ex, By are more sensitive to conductor than resistor.
- Ex is more sensitive to resistor (than By and Bz).

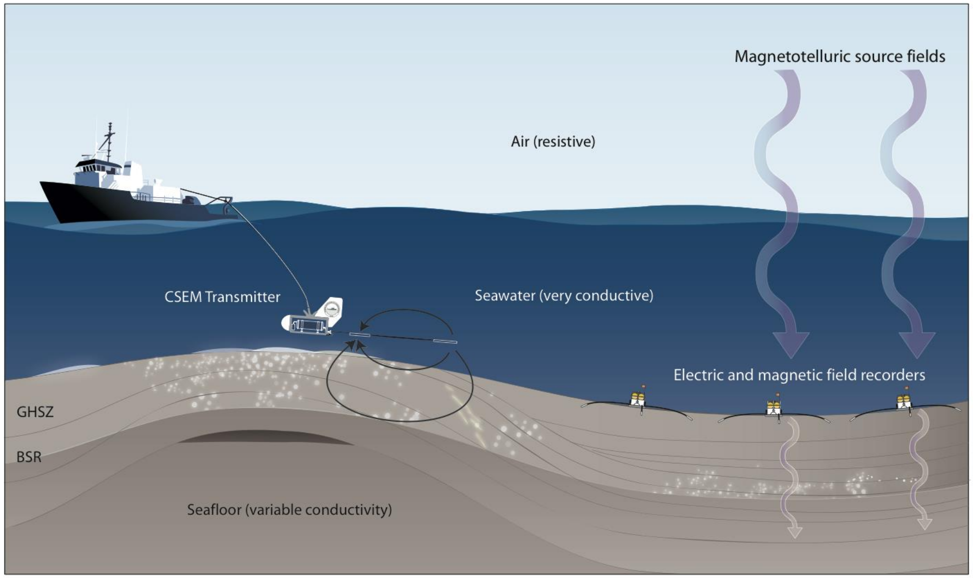
- To look for a resistive target, E-field measurements are more useful.

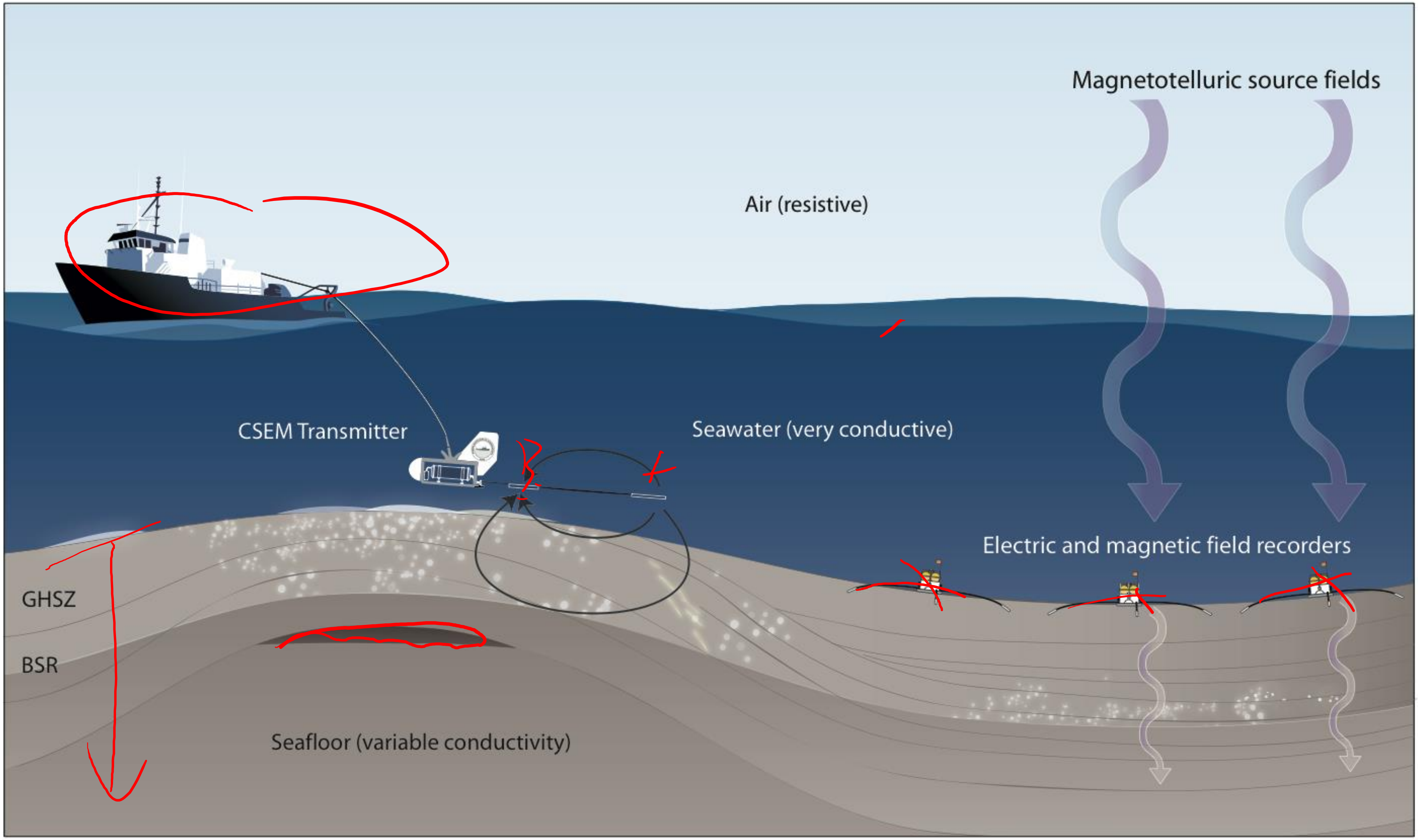
- Finding resistors is more challenging than conductors, but with grounded sources, we now can find resistors!!

Controlled-Source Marine EM (CSEM)

Application areas

- Oil and gas
- Submarine massive sulfide (SMS)
- ~~Methane hydrates~~
- Tectonic studies
- Offshore UXO
- Offshore groundwater

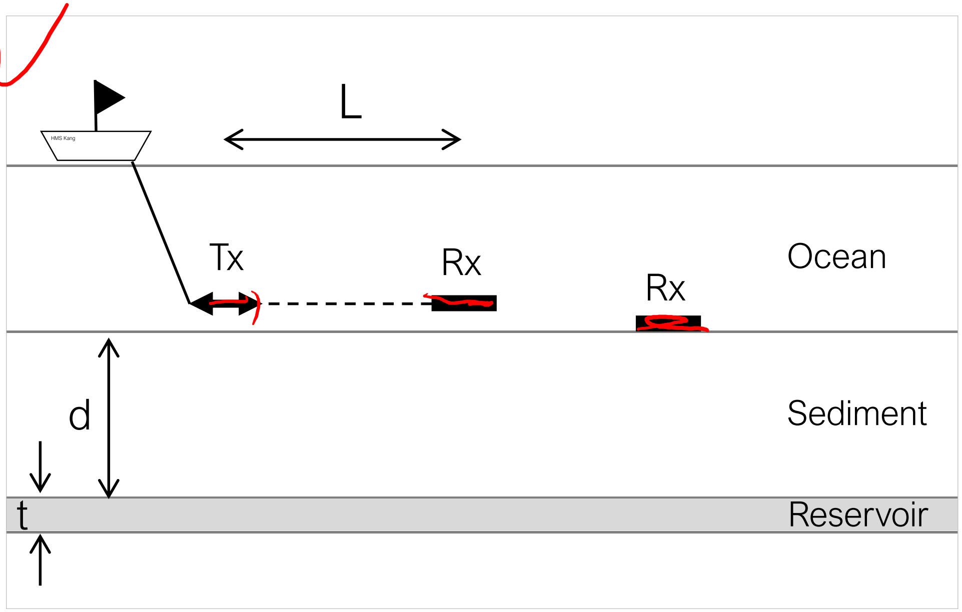


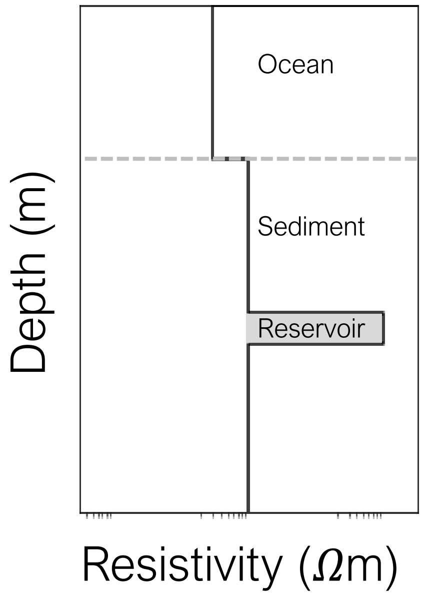

Magnetotelluric source fields
Air (resistive)
CSEM Transmitter
Seawater (very conductive)
Electric and magnetic field recorders
GHSZ
BSR
Seafloor (variable conductivity)

Application with physical properties

	ρ (Ωm)	σ (S/m)
Seawater	0.25-0.31 (15-3 ^{o}C)	3.3-4
Freshwater	100-1000	0.001-0.01
Sediment	1-5	0.2-1
Hydrocarbon	~100	~0.01
Hydrate	2000 (0 ^{o}C)	0.005
Massive sulfides	0.01-1	1-100

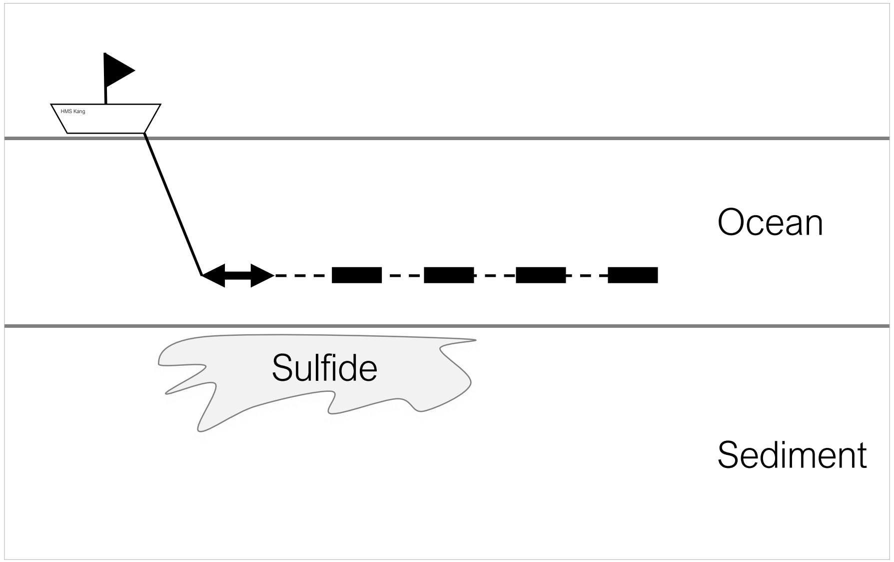
Resistive target: hydrocarbons

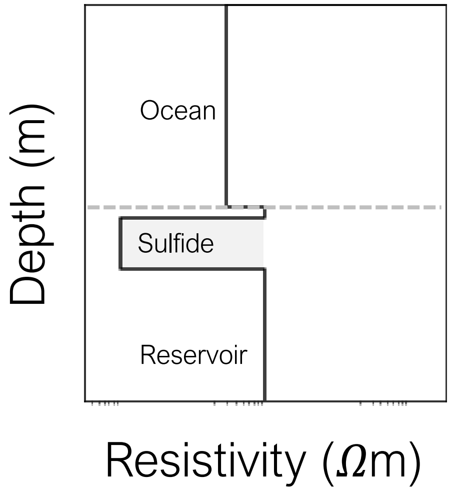


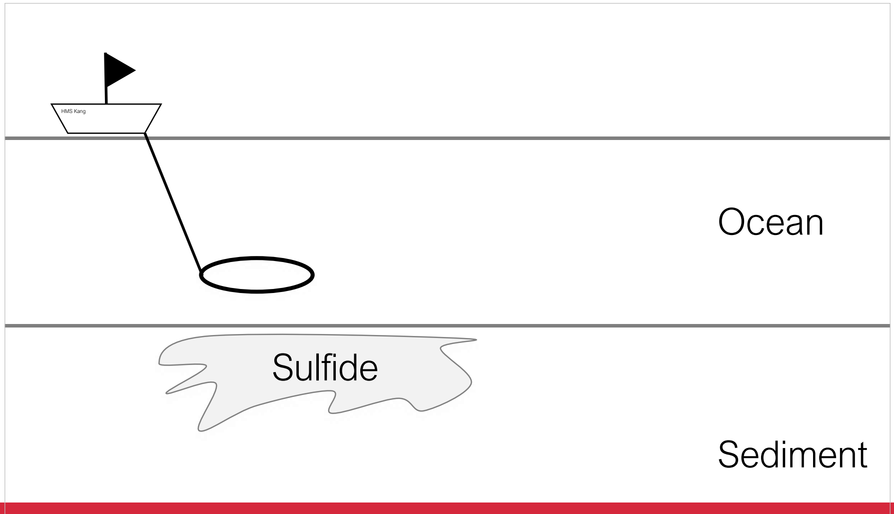


- Finding resistor: grounded source
- Deep target
  - Long offset between Tx and Rx
  - Depth of investigation ~1/3 Tx - Rx offset

Conductive Target: Massive sulfide



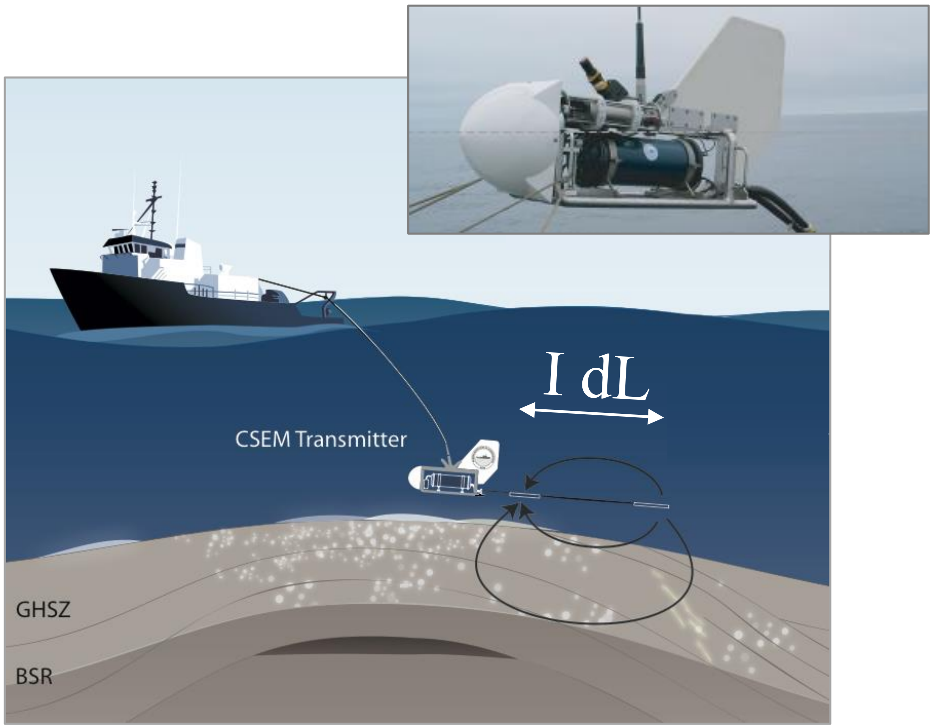




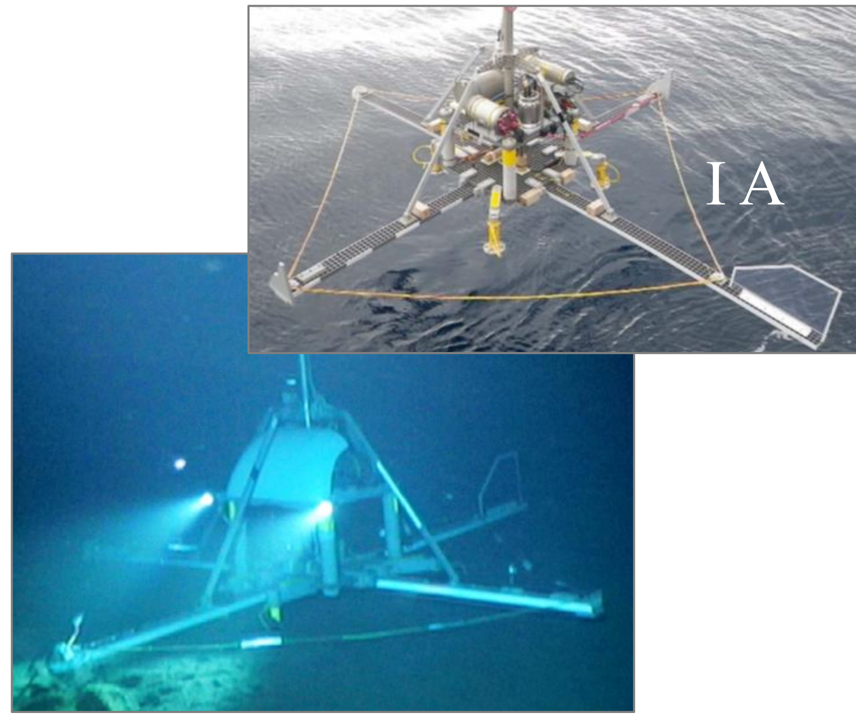
- Galvanic source
  - Towed E-field receivers
- Inductive source
  - Towed on ROV
  - db/dt sensors (coil)

Transmitters

Galvanic (Scripps: SUESI)



Inductive (Waseda Univ., GEOMAR)



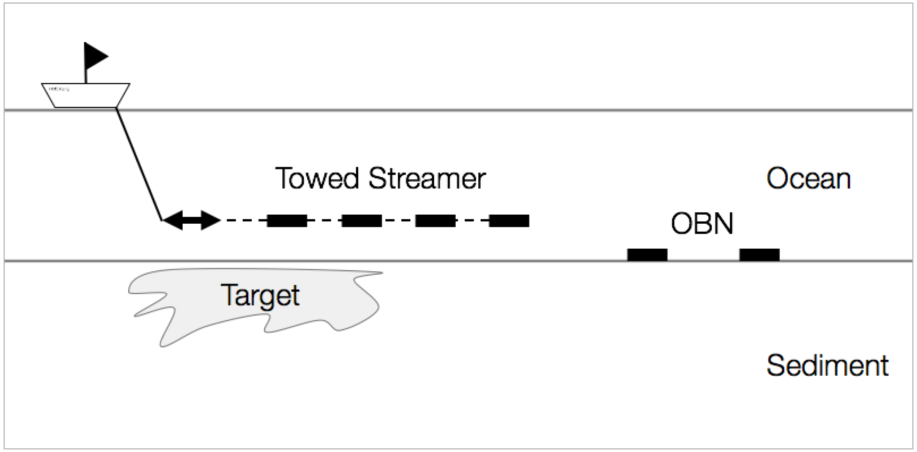
Geometric Decay $\frac{1}{r^3}$

EM Attenuation $\delta = 500\sqrt{\frac{\rho}{f}}$

Receivers

Data

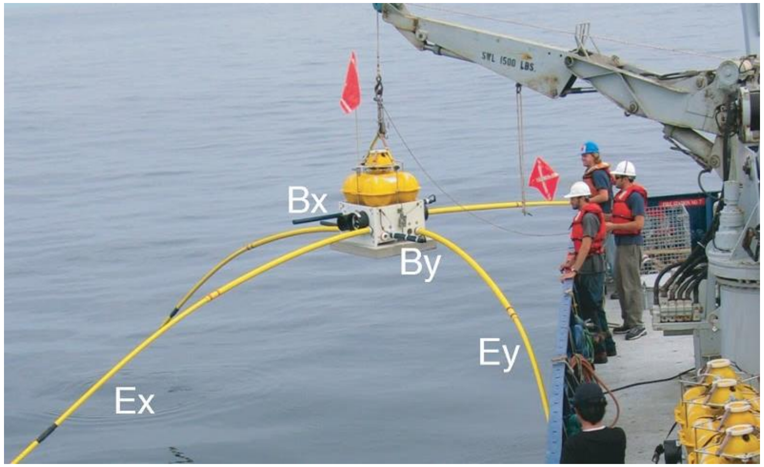
- Ex, Ey, (Recently: Ez)
- Bx, By, Bz



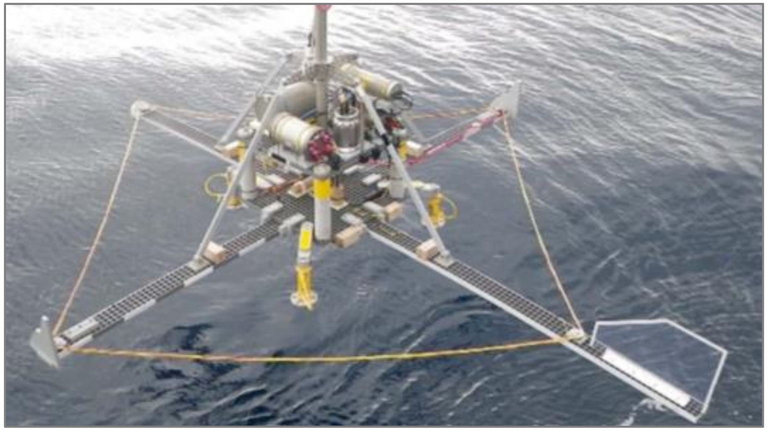
Common Systems

- Scripps: Vulcan and Porpoise
- PGS
- EMGS

Ocean Bottom Nodes (Scripps, EMGS)

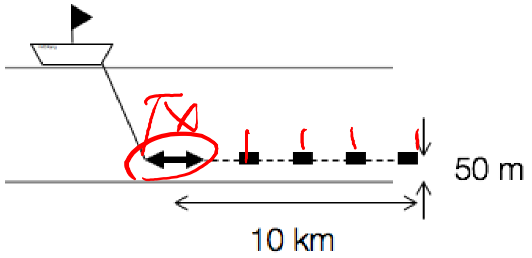


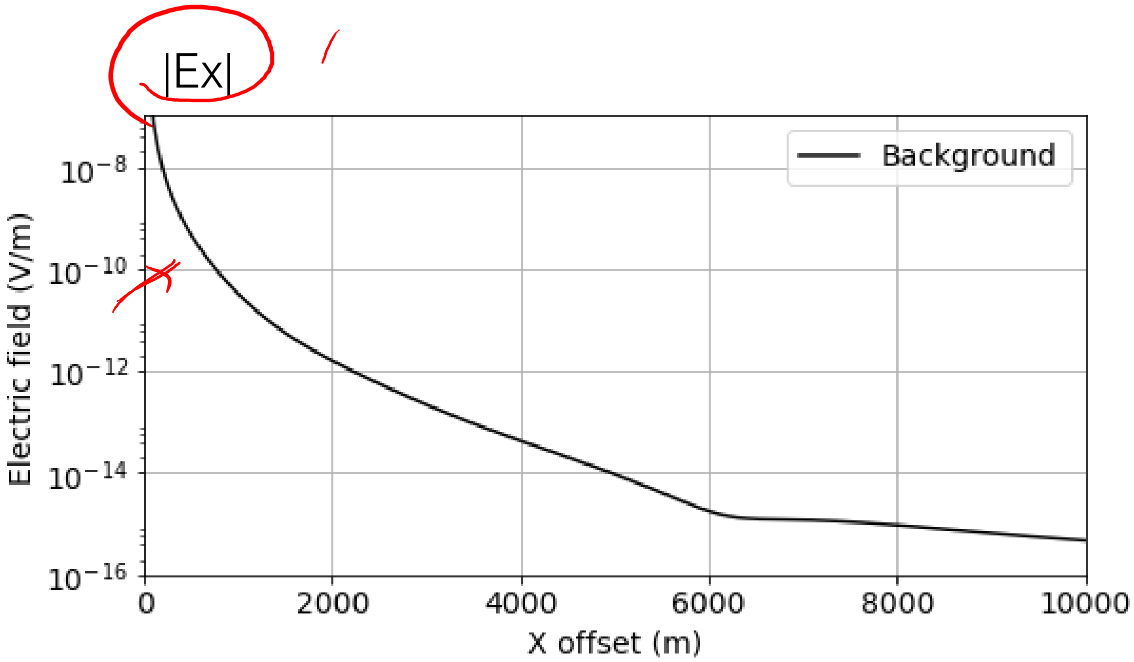
Inductive Loop (Waseda Univ)

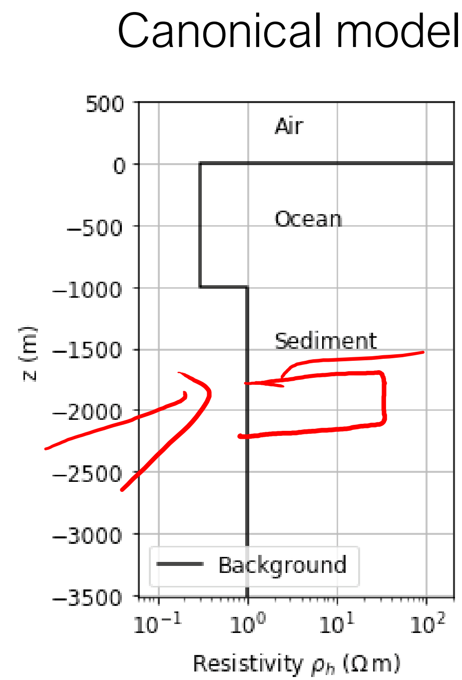


Marine CSEM: Hydrocarbons

- Towed electric dipole streamer
  - Long offset range (500m-10 km)
  - Frequency: 0.5 Hz







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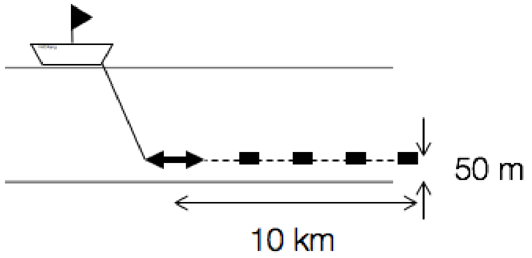
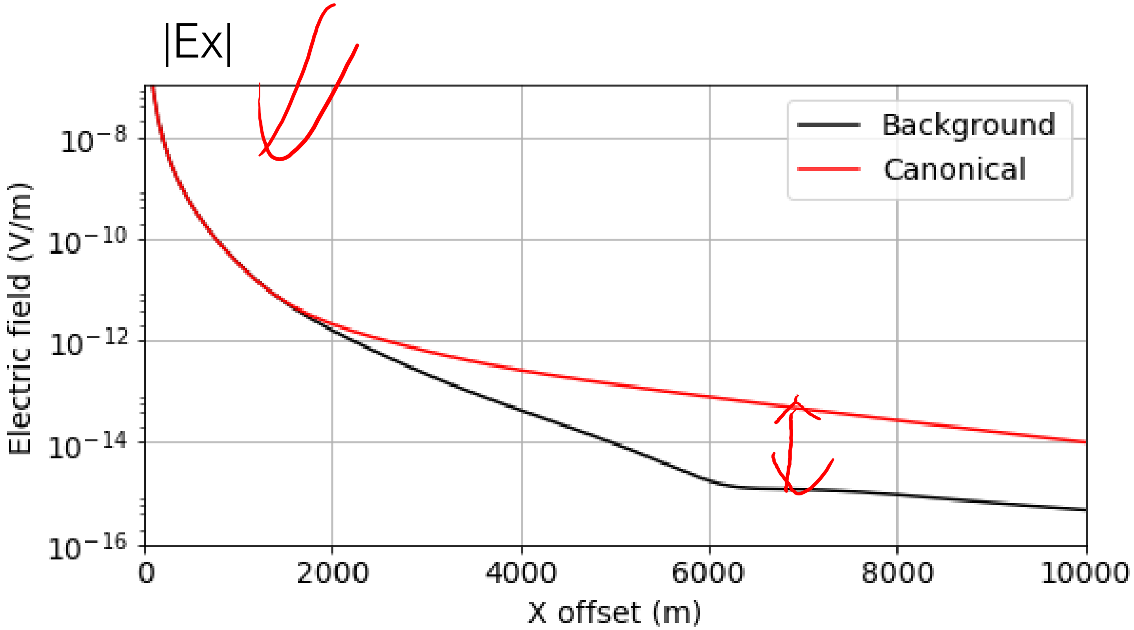
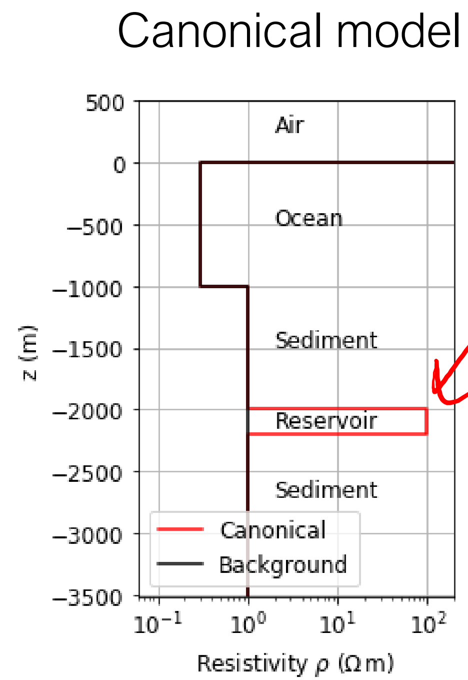




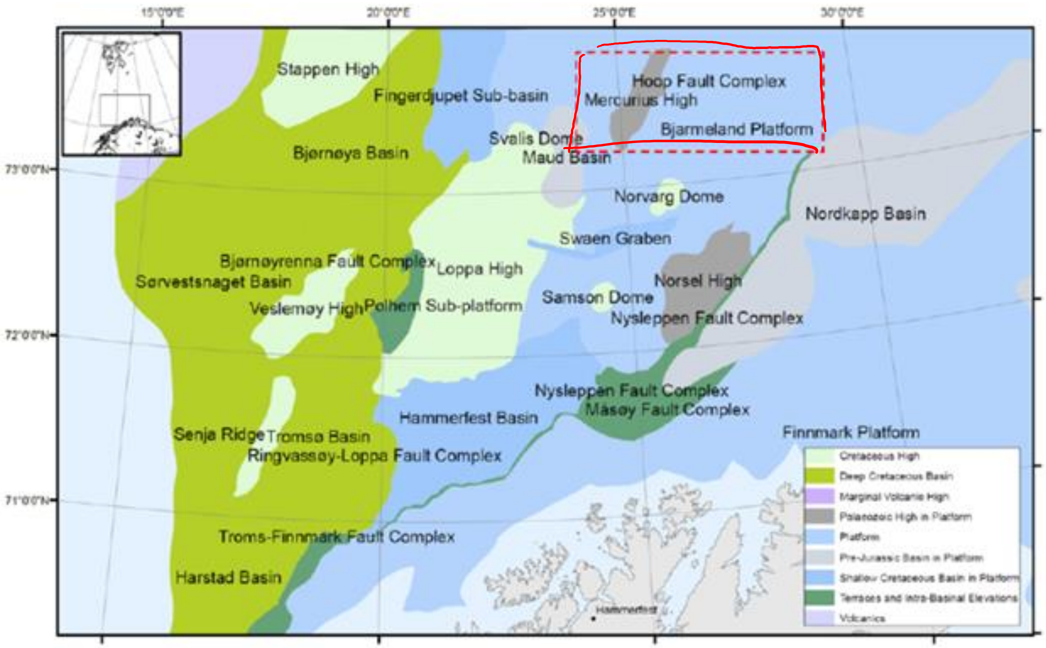


Case History: Barents Sea

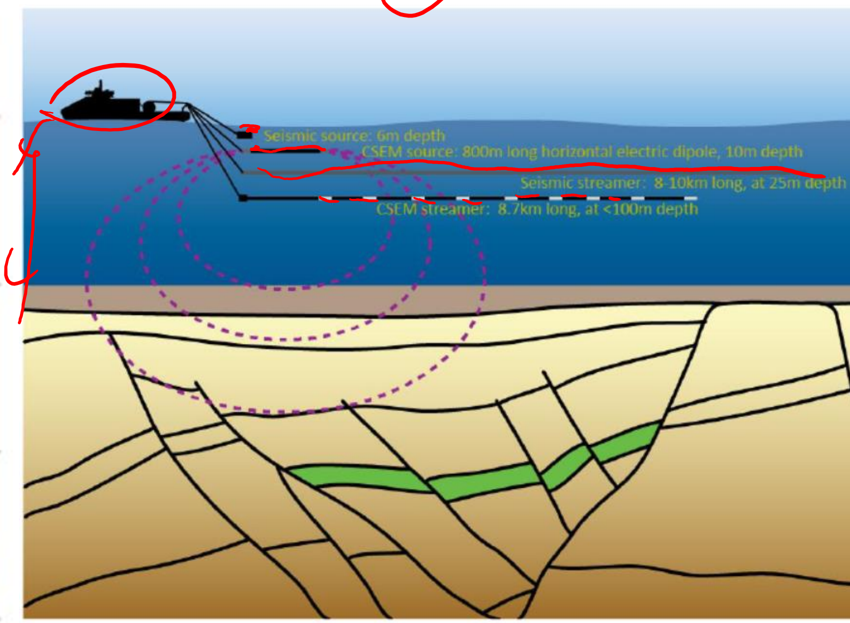
Alvarez et al., 2016. Rock Solid Images

Setup

Hoop Fault Complex, Barents Sea

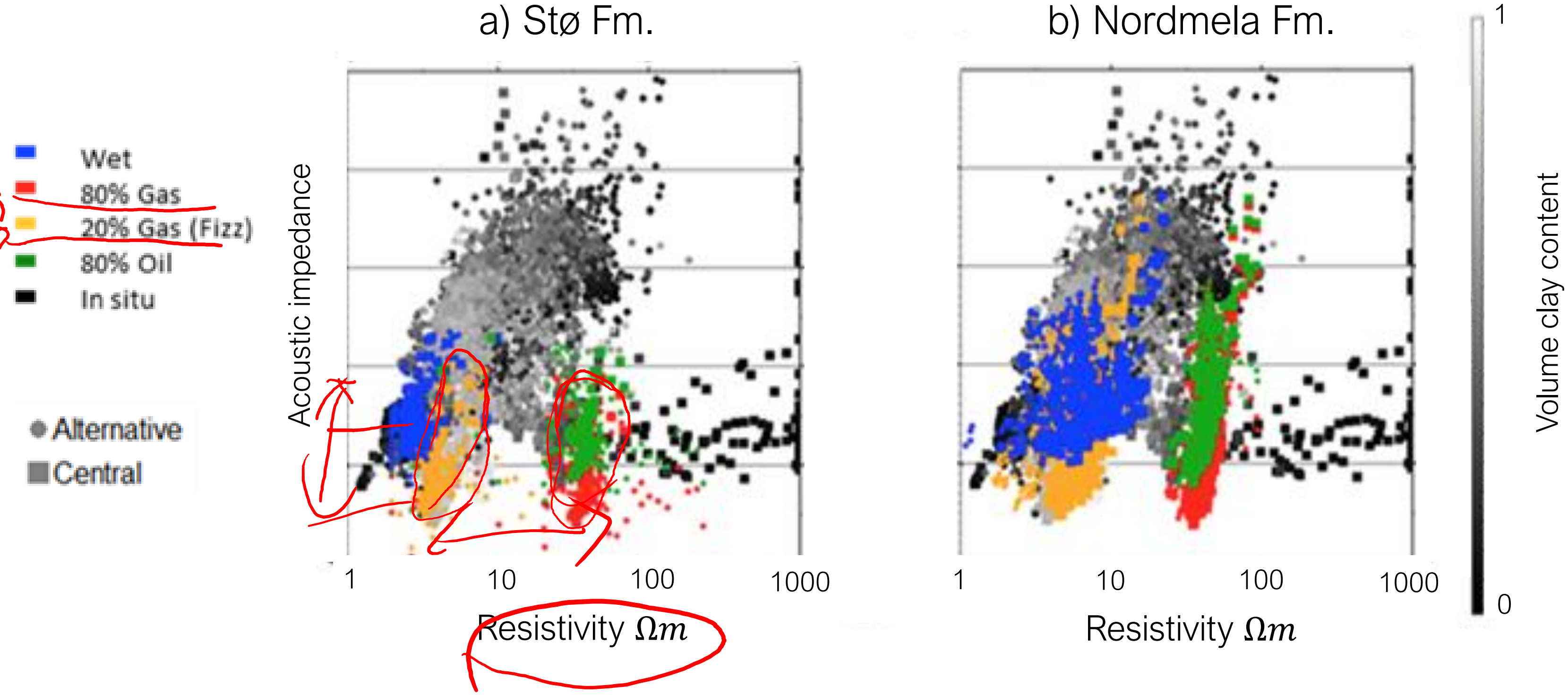


Marine CSEM



- Known hydrocarbon reservoirs within the Hoop Fault Complex, Barents Sea.
- Seismic can locate oil and gas reservoirs but cannot always determine hydrocarbon saturation (in particular fizz gas)
- Seismic, borehole and CSEM data used to characterize reservoir
  - fluid, porosity, clay content, and hydrocarbon saturation

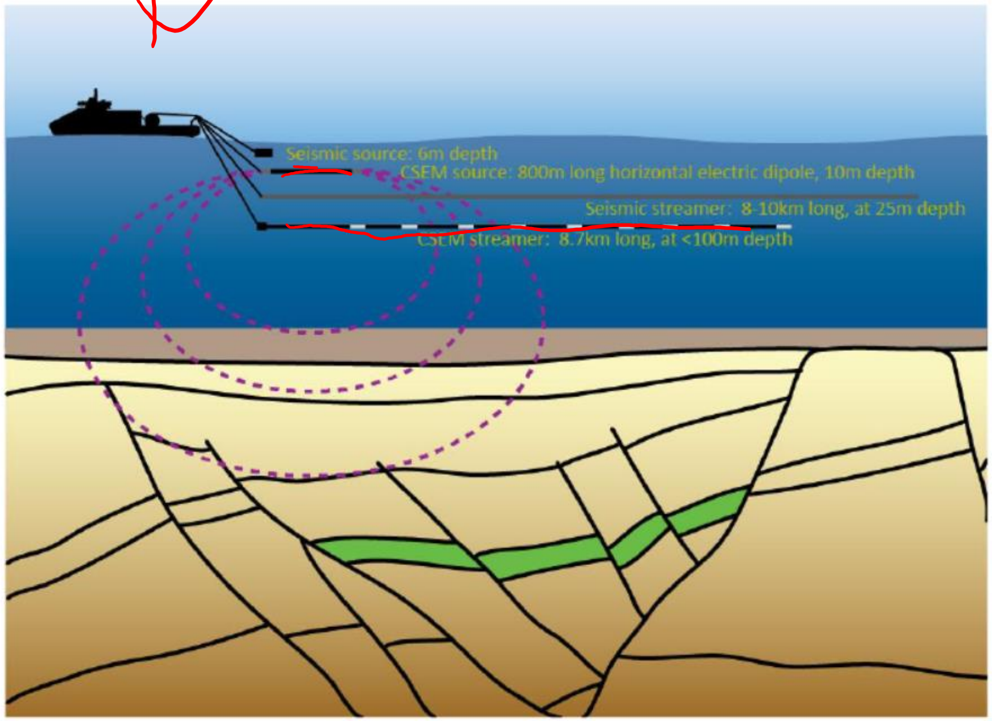
Properties



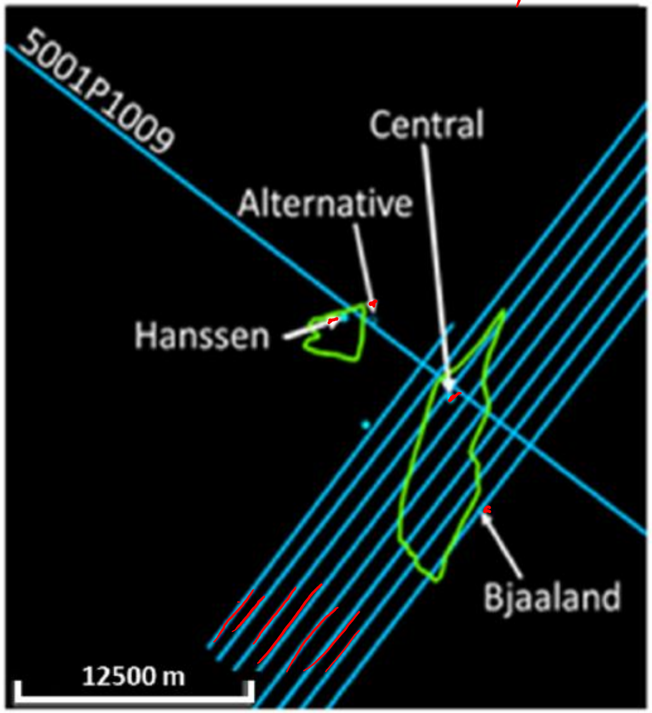
- Highly hydrocarbon-saturated reservoir (< 30% water-wet) significant resistivity
- CSEM can differentiate high from low quality reservoirs

Survey

Towed CSEM and 2D seismic



Survey lines

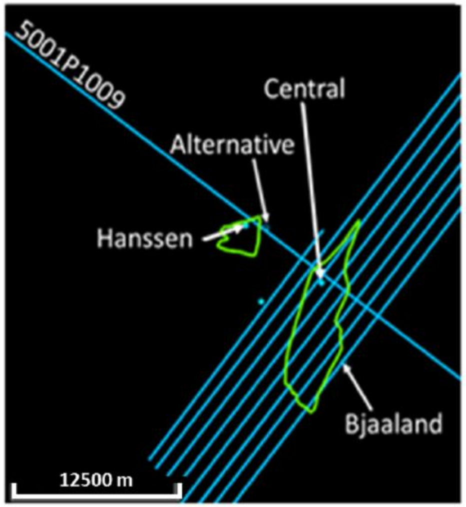


- 6 lines of 2D seismic and towed streamer CSEM data.
- 72 receivers collected CSEM data
  - offsets from 31m to 7.8 km
- CSEM frequencies: 0.2 Hz to 3 Hz.

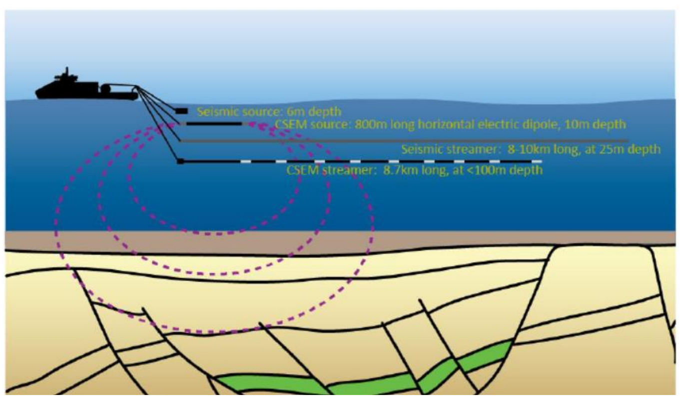
Alternative	Control well, dry
Central	Control well, productive
Hanssen	Validation well
Bjaaland	Validation well

CSEM Data

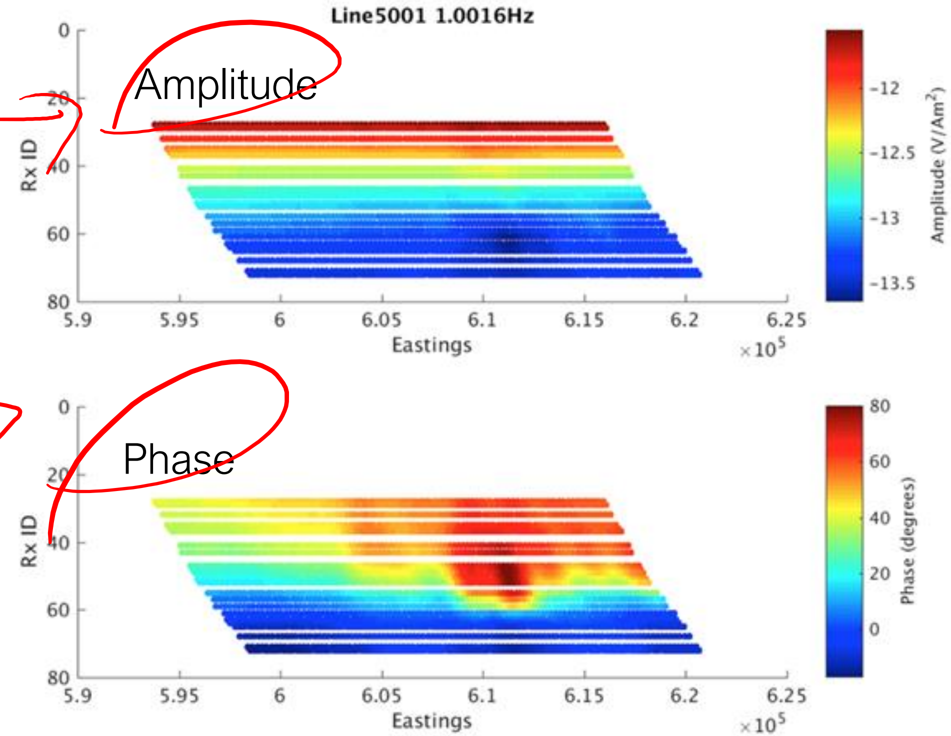
Survey lines



Towed-streamer EM



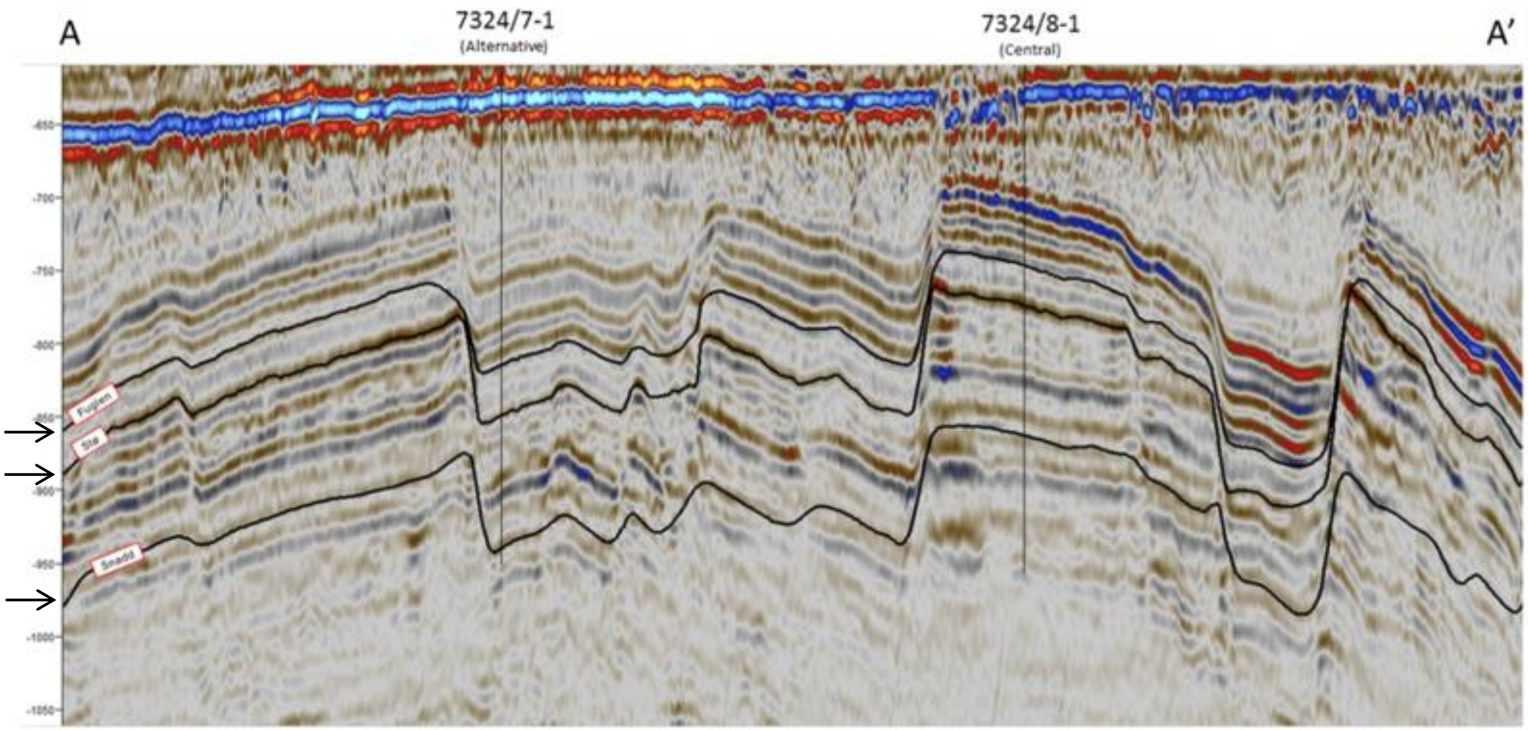
CSEM data over central reservoir (1 Hz)

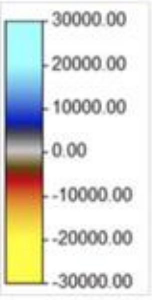


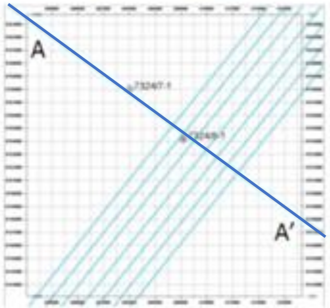
- Significant phase response over Central reservoir

Seismic data

Seismic section: Line 5001





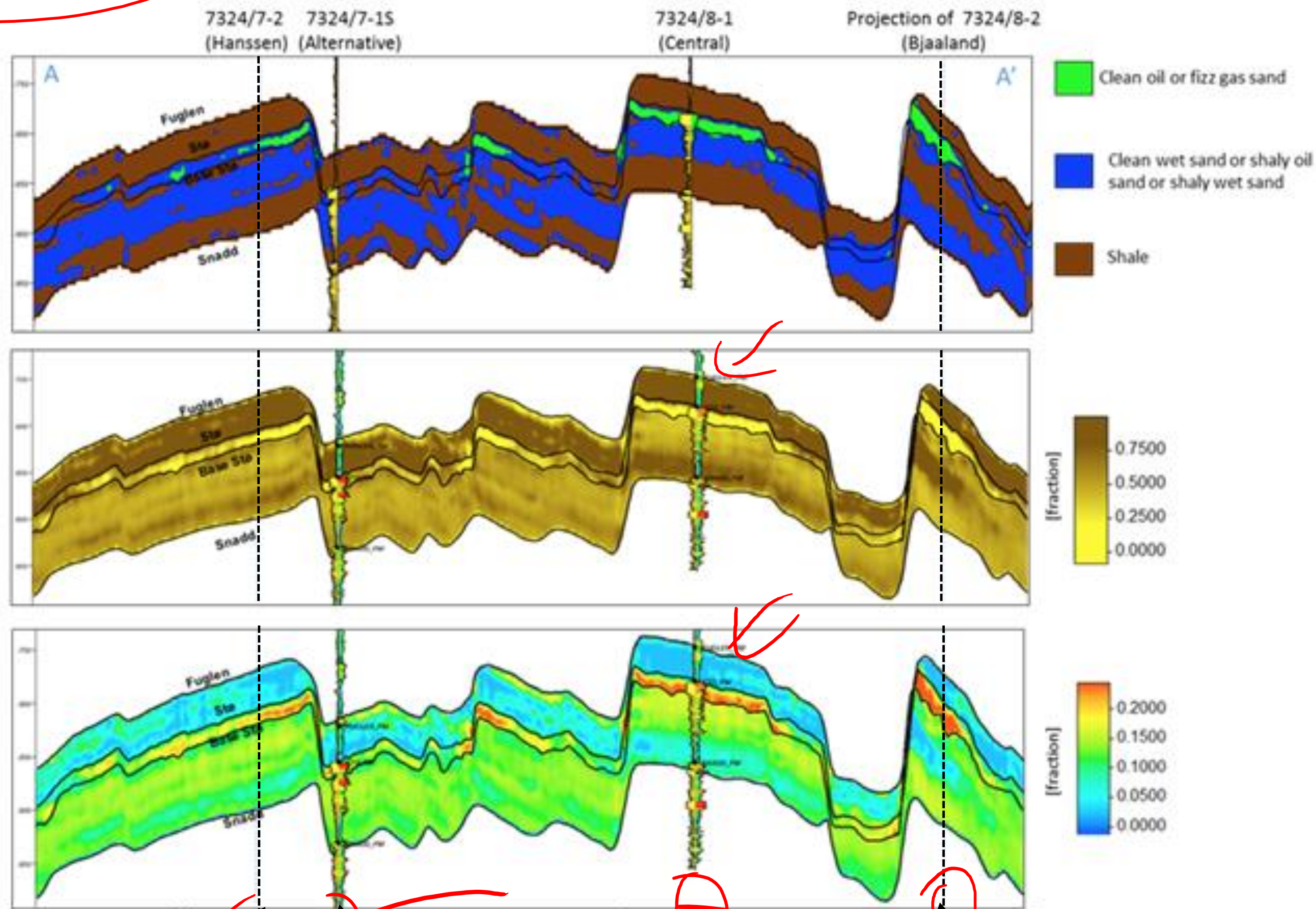


Well-Log and Seismic Inversion

Litho-fluid Facies

Clay Content

Total Porosity



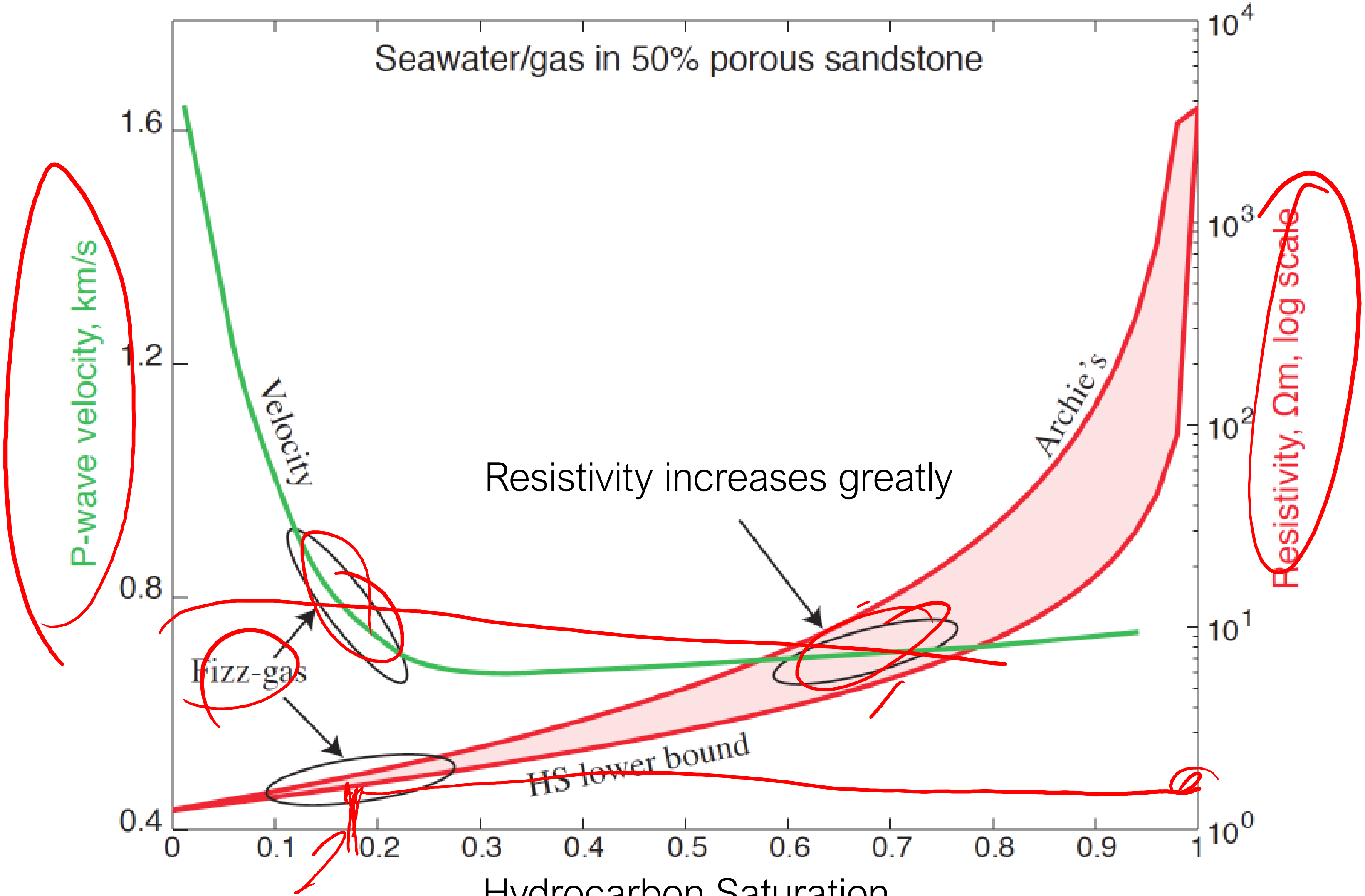
Hanssen
Validation well

Alternative
Control, dry

Central
Control, productive

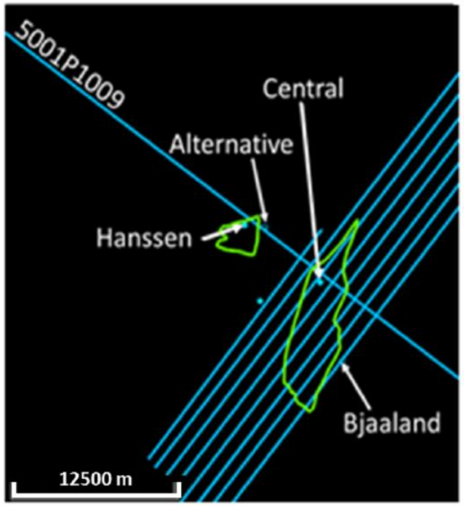
Bjaaland
Validation well

Revisiting physical properties

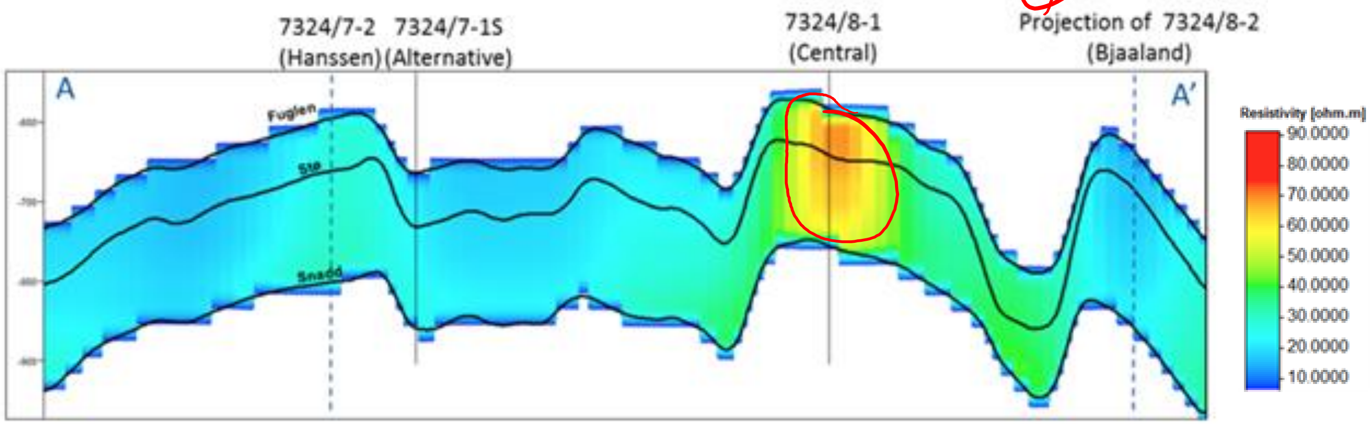


Processing: CSEM Inversion

Survey lines



Vertical resistivity section along profile line 5001



Hanssen
Validation well

Alternative
Control, dry

Central
Control, productive

Bjaaland
Validation well

- Inversion shows strong resistor at Central and a secondary resistor at Hanssen.

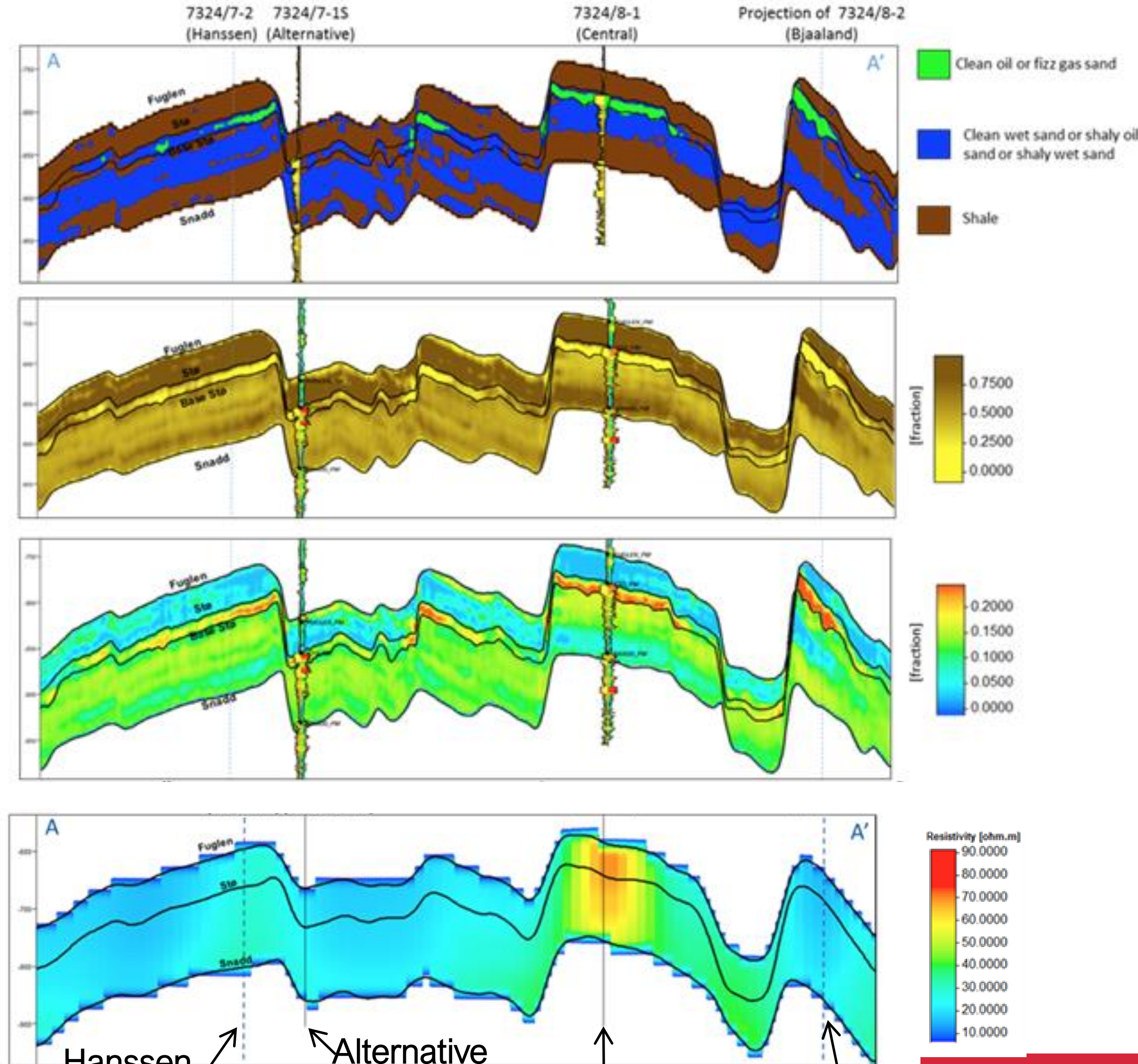
Processing: Multi-physics

Litho-fluid Facies

Clay Content

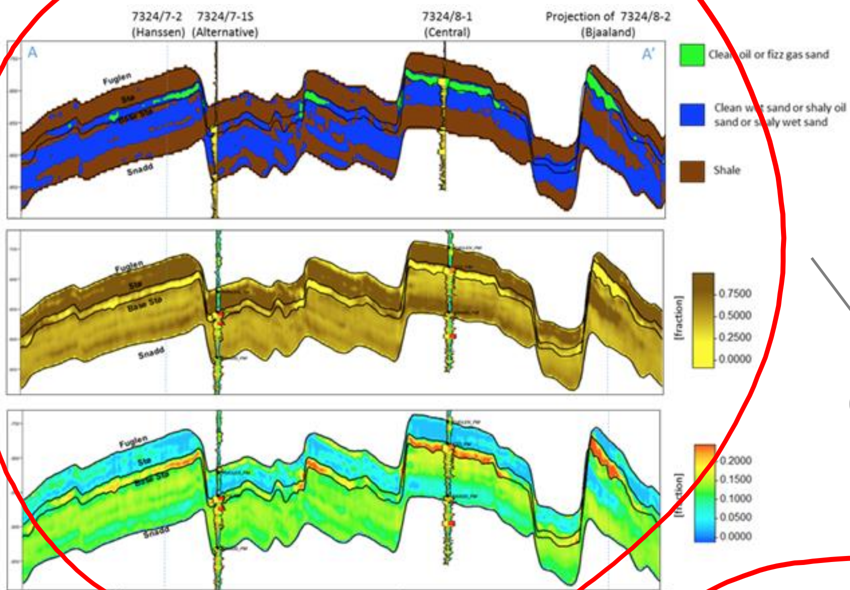
Total Porosity

Resistivity

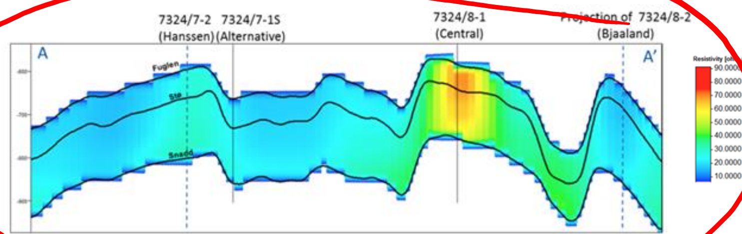


Interpretation & Synthesis

Seismic

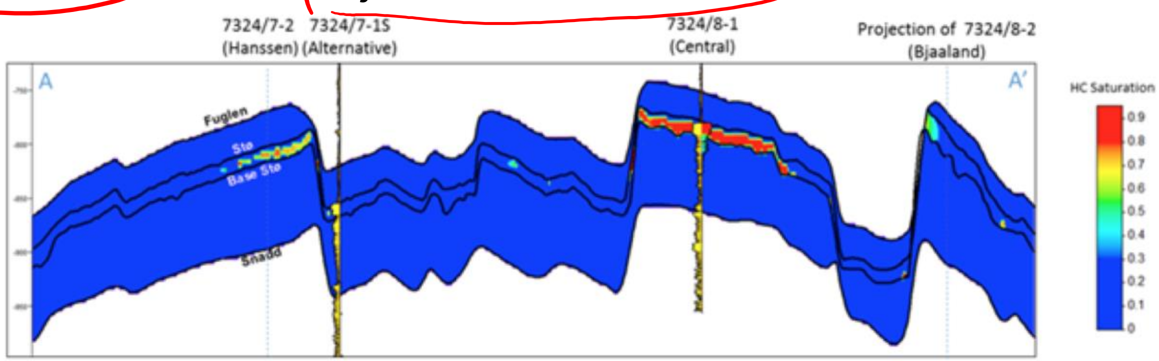


EM



+

Hydrocarbon saturation



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